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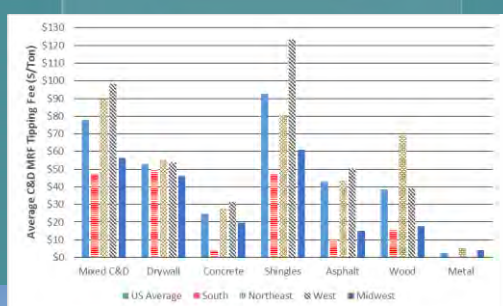
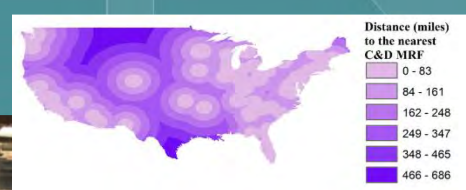
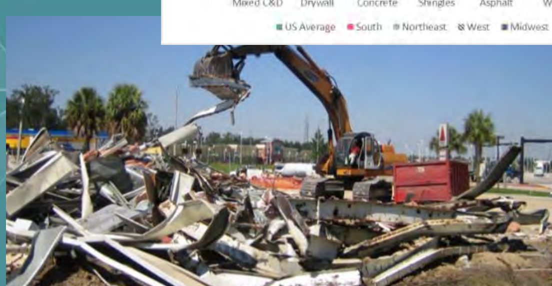
The State of the Practice of Construction and Demolition Material Recovery

Final Report







Office of Research and Development
National Risk Management Research Laboratory
Land and Materials Management Division

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The State of the Practice of Construction and Demolition Material Recovery

Materials Management Branch
Materials Management and Land Division
National Risk Management Research Laboratory
Office of Research and Development
Cincinnati, OH

Foreword

The U.S. Environmental Protection Agency (USEPA) is charged by Congress with protecting the nation′s land, air, and water resources. Under the mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, US EPA′s research program is providing data and technical support for solving environmental problems today and building the scientific knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency′s center for investigating technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory′s research program is on methods and their cost-effectiveness for preventing and controlling pollution of air, land, water, and subsurface resources; protecting water quality in public water systems; remediating contaminated sites, sediments, and ground water; preventing and controlling indoor air pollution; and restoring ecosystems. NRMRL collaborates with public and private sector partners to foster technologies that reduce the cost of compliance and anticipate emerging problems. NRMRL′s research provides solutions to environmental problems by developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory′s strategic long-term research plan. It is published and made available by USEPA′s Office of Research and Development to assist the user community and to link researchers with their clients.

Cynthia Sonich-Mullin, Director
National Risk Management Research Laboratory

Executive Summary

Construction and demolition debris (C&D) represents one of the most substantial sources of discarded materials in the United States (USEPA, 2015b). Therefore, its management plays a critical role in developing national, state, and local sustainable materials management (SMM) initiatives. Primary C&D management strategies in the United States currently include landfilling and recovery, with various external factors contributing to the relative amount managed through each pathway. As used in this report, the term "recovery" refers to and may be used interchangeably with one or a combination of several material management options including reuse, recycling, and energy recovery. Consisting primarily of concrete, asphalt, wood, metal, gypsum, soil, and vegetative material, C&D offers a strong potential for recovery, which in turn holds promise for a range of associated environmental, economic, and social benefits. However, of foremost importance is that recovery is conducted in a protective manner that does not pose a hazard to human health or the environment.

Study Purpose and Objectives

This report summarizes the current state of the practice regarding C&D recovery in the continental the United States, and the economic, community, and material-specific factors that influence the rate of C&D recovery. This report was developed to provide a resource to those interested in incorporating C&D recovery as an element of an SMM program. The information presented in this report is observational in nature and is not intended to provide regulatory interpretation or to recommend best practices for C&D recovery or approved uses for materials recovered from C&D. Rather, the objective of the report is to give the reader a fundamental understanding of the current state of the C&D recovery practice and the drivers that help shape it.

Study Design

The information presented in this report is heavily based on first-hand observations made during visits to numerous C&D processing facilities and conversations with facility owners, operators, and other members of the C&D recovery industry. This study seeks to address the following research questions, which form the basis for how the report is organized:

I. How are materials recovered from C&D managed? Sections 1 and 2 of this report summarize the properties of the C&D stream, the conventional processing of C&D, and the traditional end markets for recovered C&D.

II. What are some key factors that influence C&D recovery? Sections 3 and 4 describe some of the key factors that affect C&D recoveries such as economics, state and local policies and directives, and the impact of green building programs.

III. What are some key environmental and human health considerations associated with C&D recovery? Section 5 highlights the potential for cross-contamination as a special consideration during the recovery process as well as underscores the essential practices recyclers can undertake to reduce exposure as well as the transfer of contaminants when C&D is recovered.

C&D Management

C&D Characterization

C&D flow in the United States is not currently measured uniformly, but estimates suggest that 230 million to 530 million tons of C&D are produced nationwide each year, with anywhere from 30 to 70% being recovered (USEPA, 2015a, 2015b). The composition of this stream can vary dramatically by source, activity, and geographic region. Significant amounts of concrete and asphalt result from construction, repair, and maintenance of our nation′s transportation infrastructure (roads, bridges). Data (e.g., National Asphalt Pavement Association Asphalt Pavement Industry Surveys, United States Geological Survey Mineral Commodity Summaries for Stone [Crushed]) indicate that much of this material is recycled. Building construction, demolition, and renovation result in the generation of a mixture of building-related C&D, including wood, roofing, drywall, and concrete. While C&D is recovered in some regions, landfilling is still very common in many areas. The properties of the generated and recovered C&D stream in the United States are discussed further in Section 1 of this report.

Typical C&D Processing

Construction and demolition contractors use various techniques to separate, recover, and recycle C&D. In select cases, buildings are deconstructed to recover components (e.g., dimensional lumber, bricks) that can be reused in new projects. Most recovered C&D finds its way to some C&D processing facility. Concrete crushing operations accept relatively clean concrete (and similar materials) that have been separated at the project site and process it to produce new products. To a much smaller extent, other material-specific processing facilities accept and process additional segregated materials, such as wood or land-clearing debris (LCD), non-asbestos asphalt shingles, and drywall to produce saleable products. Asphalt paving contractors recover and recycle asphalt pavement, taken out of service, as an ingredient in the making of new asphalt pavement. Mixed C&D materials recovery facilities (MRF) accept commingled C&D and use a combination of mechanical equipment and manual labor to separate materials and process them into a more marketable form. The business model for these facilities involves charging a tipping fee for material acceptance and then diverting as much of the material from landfill disposal as possible by creating value-added products.

Traditional End Markets for Recovered C&D

Markets and the associated market values for recovered C&D vary by material type. Portland cement concrete is typically crushed and used as a replacement for construction stone in various applications, with road base being a primary use. The market viability of concrete crushing operations relies heavily on the availability and cost of local aggregates. In some regions, these facilities charge a nominal tipping fee for material acceptance, or in locations where recycled concrete products are in high demand, the material is accepted free of charge. Currently, the primary markets for wood recovered from C&D activities are boiler fuel and landscape mulch. Drywall is recycled as an ingredient for the manufacture of new drywall in a few regions of the country, while in other areas, the primary market for recovered gypsum is for agricultural products. The hot mix asphalt paving industry has evolved into the dominant market for non-asbestos asphalt shingles. The state of the practice of material recovery and C&D material markets is discussed in greater detail in Section 2.

Factors that Influence C&D Recovery

Economics, public policy, corporate policy, and material markets all play critical roles in how C&D is managed across the United States, and a review of these drivers may be informative to community decision-makers. These factors are interrelated. For example, the typical first party to make a C&D management decision is the C&D contractor. Economics may primarily influence the contractor's decisions, but local and regional public policies, the corporate policies/goals of the client (if applicable), and the status of the area′s C&D material markets all have financial implications on the final management strategy selected by the contractor.

Location-Specific Conditions

Labor rates and the availability of space for material storage also influence the type of C&D management option chosen by the contractor at the job site. High labor rates and crowded (e.g., urban) work conditions may favor more traditional demolition practices, whereas low labor rates and ample workspace may favor onsite C&D material segregation, onsite reuse of inert/clean fill materials, and possibly deconstruction efforts. Longer distances from the point of C&D generation to a C&D recovery facility (compared to a landfill) makes a recovery less feasible in many regions of the country. In some cases, the high cost of landfill disposal fosters C&D recovery, especially for mixed C&D streams. Regional design and construction practices for landfills, along with location-specific requirements related to materials disposal, play a role in a landfill's tipping fee structure.

Public and Corporate Policy

Public policy can also play a significant part in promoting C&D recovery. As C&D represents one of the larger components of the solid waste stream, establishing state solid waste recovery goals has prompted many regions to target C&D for recovery initiatives. Local government policy directives for contractors to achieve recovery goals, or that provide incentives for utilizing certified recovery operations, also have been shown to increase a state's recovery rate. C&D recovery rates have increased in some areas of the country following the banning or restricting of C&D from landfills. Similarly, the corporate policy also can impact the prevalence of C&D recovery (e.g., a corporation requiring that new buildings be Leadership in Energy and Environmental Design [LEED] certified).

Materials recovered from C&D have multiple end markets, but the dominance of one or two end uses is typical. The reduced availability and price of virgin materials often play a major role determining which market is most attractive. For example, when natural aggregates for construction are less abundant, concrete recovery is more appealing. When construction specifications requiring the use of recovered materials in new construction are required for all state-level projects (e.g., a specification for the use of recovered asphalt shingles in new asphalt pavement by a state or local transportation department), thriving markets often result. The economic, public and corporate policies and material market factors that influence the frequency and type of C&D recovery that occurs across the United States are discussed in greater detail in Section 3.

Green Building Programs

An additional driver for increased C&D recovery is green building certification. Green building certification programs have helped underscore the environmental impacts associated with the disposal of building materials. A notable example is the U.S. Green Building Council's LEED certification program. Sound material and resource utilization through the reuse and recycling of C&D and the use of recycled-content building materials help achieve the green building certification. Therefore, LEED and other programs are believed to have fostered the growth of C&D material recovery and the development of markets for recovered C&D. The features and impacts of green building programs are discussed in greater detail in Section 4 of this report.

Environmental and Human Health Considerations Associated with C&D Recovery

C&D recovery achieves numerous environmental benefits (e.g., landfill waste diversion, resource and energy savings, reduction in greenhouse gas emissions), but care must be exercised to properly manage constituents of potential concern in some materials recovered from C&D. Historically, some building products contained or have had the potential to come into contact with chemicals, metals, or minerals that could cause harm or pose a risk to human health and the environment under specific exposure conditions. Notable examples include asbestos (previously used in a variety of building products), lead (a once common pigment in the paint), polychlorinated biphenyls (PCBs) (used in light ballasts, caulk, and specialty paints), and mercury (used in fluorescent lighting and electrical switches). These constituents must be handled in accordance with all applicable regulations and care must be taken to prevent cross-media contamination during material processing. For example, properly separating clean wood from preservative-treated wood reduces the potential for elevated levels of contaminants in a landscape mulch product or a fuel product, which limits the risks to human health and the environment and avoids air emission compliance issues. Possible down-chain, cross-media contamination issues are of interest to help understand and promote best practices for C&D processing and to ensure sustainable markets for recovered C&D. Environmental and human health concerns during the recovery of C&D are discussed in greater detail in Section 5 of this report.

Conclusion

The C&D recovery industry continues to grow. Some components (e.g., concrete) are commonly recovered for existing economic reasons. Other elements—especially those with low market value and that frequently require processing to separate them from the rest of the C&D stream—remain a challenge to recycle in some cases. Many state and local governments have demonstrated that public policy can play a major role in advancing C&D recovery, and municipalities or other entities interested in growing C&D recovery in their areas can reference these examples. Data gaps remain in certain areas, such as the need to better 1) track the amount, composition, and disposition of C&D in the United States, especially as related to C&D recovery; 2) compile and disseminate successful strategies for C&D recovery while emphasizing caution around certain constituents that adversely impact human health and the environment; and 3) document the benefits resulting from C&D recovery.

Notice

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ADC	Alternative daily cover
ANSI	American National Standards Institute
ASC	Assurance Safety Consulting
ASTM	American Society for Testing Materials
BREEAM	Building Research Establishment
BTU	British thermal unit
C&D	Construction and demolition debris
CAA	Clean Air Act
CA PRC	California Public Resources Code
CCA	Chromated copper arsenate
CCG	Cascadia Consulting Group
CDM	Camp, Dresser & McKee
CDRA	Construction & Demolition Recycling Association
DEQ	Department of Environmental Quality (Oregon)
DGS	Department of General Services (Sacramento, CA)
DNREC	Delaware Department of Natural Resources and Environmental Control
DOT	Department of Transportation
DSHW	Division of Solid and Hazardous Waste (New Jersey)
EEA	Executive Office of Energy and Environmental Affairs (MassDEP)
EES	Department of Environmental Engineering Sciences, University of Florida
EOL	End-of-life
EPD	Environmental Product Declaration
FAA	Federal Aviation Administration
FDEP	Florida Department of Environmental Protection
FDS	Florida Department of State
FGD	Flue gas desulfurization
FHWA	Federal Highway Administration
FSC	Forest Stewardship Council
H_2S	Hydrogen sulfide
HMA	Hot mix asphalt
HVAC	Heating, ventilation, and air conditioning
ICC	International Code Council
IDNR	Iowa Department of Natural Resources
IWCS	Innovative Waste Consulting Services, LLC
LBP	Lead-based paint
LCA	Life cycle analysis
LCD	Land-clearing debris
LED	Light-emitting diode
LEED	Leadership in Energy and Environmental Design
MassDEP	Massachusetts Department of Environmental Protection

MEA	Maryland Energy Administration
MHC	McGraw-Hill Construction
MPCA	Minnesota Pollution Control Agency
MRF	Materials recovery facility
MSW	Municipal solid waste
NAHB	National Association of Homebuilders
NAPA	National Asphalt Pavement Association
NCHRP	National Cooperative Highway Research Program
n.d.	No date
NGBS	National Green Building Standard
NJ DEP	New Jersey Department of Environmental Protection
NSF	National Science Foundation
OGS	Office of General Services (New York)
OVE	Optimal value engineering
PCB	Polychlorinated biphenyl
PCC	Portland cement concrete
PPE	Personal protective equipment
RAP	Reclaimed asphalt pavement
RAS	Recycled asphalt shingles
RCA	Recycled concrete aggregate
RCRA	Resource Conservation and Recovery Act
RDF	Refuse-derived fuel
RI DEM	Rhode Island Department of Environmental Management
RSM	Recovered screened material
SMM	Sustainable materials management
SPU	Seattle Public Utilities
SWALCO	Solid Waste Agency of Lake County, Illinois
SWANA	Solid Waste Association of North America
SWRCB	State Water Resources Control Board
TRDI	Texas Recycling Data Initiative
TNRCC	Texas Natural Resource Conservation Commission
U.S.	United States
USDA	United States Department of Agriculture
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
USGBC	United States Green Building Council
USGS	United States Geological Survey
VOC	Volatile organic compound
WBJ	Waste Business Journal
WMA	Warm mix asphalt
WSDOT	Wisconsin Department of Transportation
XRF	X-ray fluorescence

1. INTRODUCTION

1.1 Objectives and Organization

The objective of this report is to summarize the current state of construction and demolition debris (C&D) recovery in the United States. This report is intended to provide information to those interested in incorporating C&D recovery as an element of a sustainable materials management (SMM) program. Note that while C&D recovery and reuse is encouraged, and may serve as a valuable component in meeting material recovery goals, it must be conducted in a protective manner that does not pose a hazard to human health or the environment. This report summarizes 1) how materials recovered from C&D are currently used, and, 2) factors, including policy approaches, that may impact C&D recovery rates in a community. This report is intended to facilitate an exchange of technical information and does not constitute an endorsement of a specific end use or a recommendation for the implementation of a specific policy approach.

Various factors affecting C&D recovery were examined, including:

- systems and technology used to facilitate C&D recovery and processing;
- economic factors that may inhibit or enable recovery of C&D in a particular region or market;
- public and corporate policy approaches to increase C&D recovery, such as C&D recovery initiatives and incentives;
- impacts of green building practices and economics; and,
- examples of environmental and health and safety considerations.

The report is organized into seven sections:

- Section 1 defines the report's objectives and organization, and provides background information on C&D generation and landfilling in the United States.
- Section 2 describes C&D recovery, detailing how the major types of materials recovered from C&D are commonly processed, and the traditional end markets for recovered C&D.
- Section 3 reviews the impacts of economic, public policy, corporate policy, and material market factors on recovery rates.
- Section 4 provides an overview of green building materials, focusing on existing green building certification programs, processes, and waste management requirements. It

includes information on the recyclability of green building materials relative to conventional building products.

- Section 5 discusses the potential environmental and health impacts of the recovery and reuse of C&D with a focus on the potential for cross-media contamination of several materials recovered from C&D.
- Section 6 summarizes data gaps identified during report development and opportunities for additional research that would further the understanding of C&D recovery in the United States.
- Section 7 lists the references used throughout the report.

1.2 Background

Initiatives supporting the recovery of C&D in a manner protective of human health and the environment are key elements of the sustainable end-of-life management of these materials.

EPA promotes sustainable materials management (SMM), a systemic approach to using and reusing materials more productively over their entire life cycles. It represents a shift in how our society thinks about the use of natural resources and environmental protection. By looking at a product's entire life cycle, we can find new opportunities to reduce costs and conserve resources.

The EPA non-hazardous materials and waste management hierarchy recognizes that no single waste management approach is suitable for managing all materials and waste streams in all circumstances. It ranks the various management strategies from most to least environmentally preferred, and places emphasis on reducing, reusing, and recycling as key to sustainable materials management (US EPA, 2017).

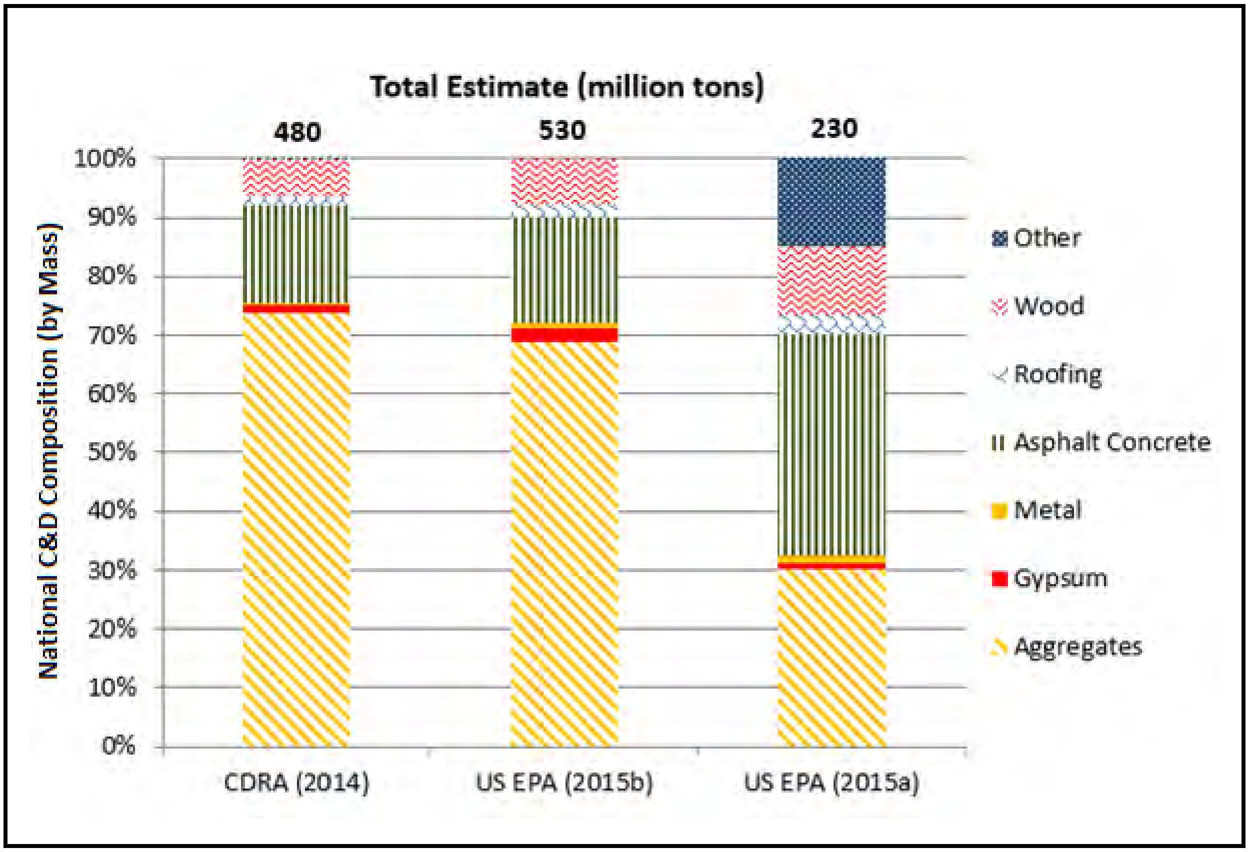
C&D consists of the materials generated during the construction, renovation, and demolition of buildings, roads, bridges, and other structures. The components of C&D vary depending on activity type and structural materials used. Broadly, the C&D stream consists of concrete, wood, metal, asphalt pavement, asphalt shingles, drywall, masonry products, land-clearing debris (LCD), and various minor constituents. C&D represents a substantial portion of the overall materials and discards generated through human activities; estimates of the amount of C&D generated range from equal to up to twice the total amount of municipal solid waste (MSW) (USEPA, 2015a, 2015b).

C&D can be recovered for direct reuse (e.g., use of recovered lumber in new construction projects), recycled into new products (e.g., C&D steel re-melted and re-cast into new steel products), utilized in other beneficial ways (e.g., crushed concrete used for road base), combusted for energy recovery, or disposed in landfills. Building-related C&D recovery and reuse practices have evolved over the past decade for numerous reasons, such as green building rating system requirements and credits, local government C&D directives, and state and local building code requirements. Although most C&D components have a high potential for recovery, large amounts of C&D remain underutilized. Barriers to C&D recovery include the relatively low price of C&D disposal, the lack of incentives, the absence of recycling markets, access and distance to recovery facilities, the lack of C&D-recovery public policy directives, and concerns about contamination with harmful materials such as asbestos, lead-based paint, or treated wood.

This report summarizes the current state of C&D recovery in the United States. Recent efforts by the U.S. Environmental Protection Agency (USEPA) have focused on describing the amount and composition of the domestic C&D stream (USEPA, 2015a, 2015b). A rigorous review of these data is not presented here. However, C&D composition and characteristics are important to understand material flows and, by extension, to gauge the opportunities to use various materials management approaches. Thus, the remainder of this section provides an overview of current U.S. C&D generation and composition, exemplifies how green buildings and green building materials have contributed to expanding the C&D recovery and the recycled C&D material market, and introduces the issue of harmful constituents in some small amount of materials in the C&D stream.

The amount of C&D generated from a given construction, demolition, or renovation project depends on different factors including project type, project size, the age of the structure, condition of the structure, and geographic location of the structure. The diverse nature of C&D generation (e.g., construction versus demolition, residential buildings versus infrastructure), coupled with limited recordkeeping requirements, makes C&D quantification and tracking a challenge. Differences in state or local public policy definitions of C&D also create a nonuniform base from which to develop national-level C&D generation and management estimates (USEPA, 2015a).

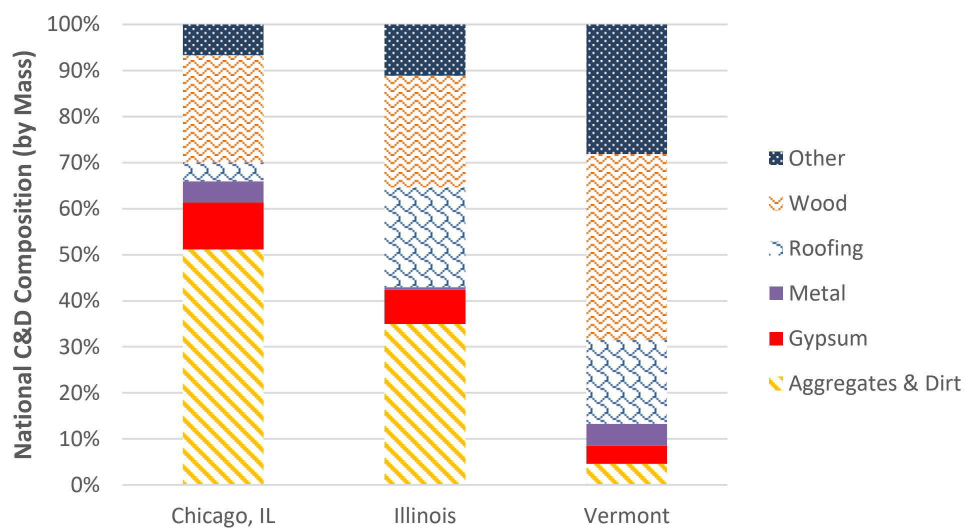
Figure 1-1 summarizes the estimated composition of C&D based on three analyses. These three estimates project U.S. C&D generation in the range of 230 million to 530 million tons per year (CDRA, 2014; USEPA, 2015a, 2015b), while two indicate that 30% to 70% of the generated stream gets recovered (CDRA, 2014; USEPA, 2015a). Variability among these estimates results from the different data sources, assumptions, and methodologies used.



Note: Aggregates consist primarily of crushed concrete, but also include masonry products.

Figure 1-1. Annual U.S. C&D Quantity and Composition Estimates

Figure 1-2 presents landfilled C&D composition data for three different locations (USEPA, 2015a). C&D composition measured as disposed of in a landfill may differ from composition estimates based on materials flow analysis or infrastructure and spending statistics (the basis for the composition estimates in Figure 1-1). Some C&D materials, notably large sources of aggregates such as concrete and asphalt pavement, never reach a landfill site as they are captured and managed in other fashions (e.g., aggregate processing facilities). Figure 1-2 shows that Chicago's C&D contains more than 50% aggregates and dirt, compared to only 35% for Illinois as a whole; the state's overall composition of landfilled C&D contains substantially more roofing material, and less metal and gypsum, compared to Chicago alone. Composition estimates from Illinois and Vermont provide an example of the differences in the landfilled C&D composition among the states. Vermont's wood fraction is nearly twice that of Illinois, and the fraction of aggregates and dirt is substantially less.



Note: Aggregates & Dirt consist primarily of concrete, but also include masonry products and soil.

Figure 1-2. Waste Composition of the C&D Stream in the City of Chicago, State of Illinois, and the State of Vermont for 2008–2009 (USEPA, 2015a)

The USEPA (2015a) estimated the composition of disposed of C&D from a compilation of C&D characterization studies. Wood, roofing materials, other materials, and concrete were the four materials disposed of in the greatest amounts (by mass), comprising about 66% of the total amount (Figure 1-3). Roofing and other material categories were found in greater fractions in landfilled C&D compared to the composition of C&D overall (Figure 1-1), possibly because these materials possess fewer recovery and diversion options.

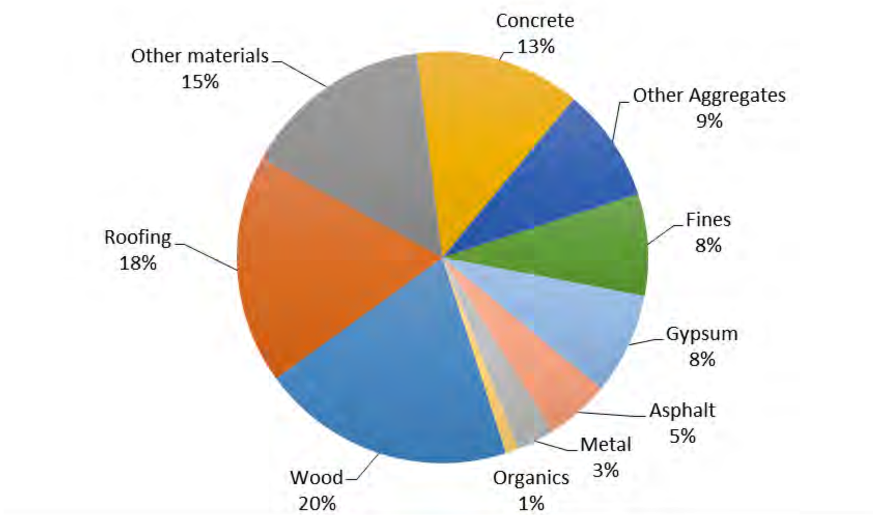


Figure 1-3. Composition Estimate of C&D Accepted at Permitted U.S. Disposal Facilities (Adapted from USEPA, 2015a)

The prevalence of C&D recovery is influenced by economic, public policy, material-specific factors and, notably, green building certification programs. An important component of most certification programs is the requirement for sound material and resource utilization through the reuse and recycling of C&D. Many green building programs also encourage the use of recycled-content building materials, which fosters the growth of markets for recovered C&D and realizes the benefits of the reuse and recycling efforts. A noteworthy example of a green building certification program is the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED). LEED v4, the current version of the program, demonstrates a significant transformation in the assessment of green building materials and continues to require the development and implementation of a C&D waste management plan. Also, points are earned through reduction of the total construction waste materials generated per square foot of the building's area or through diversion by salvage or recycling.

Several materials encountered in C&D, though only a small fraction of the overall mass of C&D, have the potential to contain hazardous constituents and thus require special attention.

The recovery of C&D presents a set of unique challenges due to the heterogeneous nature of this material stream and the occasional presence of harmful substances. Examples include wood coated with lead-based paint (LBP), fluorescent bulbs and thermostats containing mercury, and asbestos-containing materials, such as asbestos-containing floor tiles. Hazardous constituents must not be processed alongside conventional C&D. Properly trained personnel must evaluate buildings, and materials such as asbestos- and mercury-containing products and equipment should be dentified and removed before demolition. In addition, C&D directed for recovery at processing facilities are managed in a manner protective of human health and the environment. For example, C&D processors must be alert to the potential for cross-contamination from the commingling of materials, as this could introduce contaminants that might not normally be present in a source-separated stream.

1.3 Methodology, Quality Assurance, and Data Limitations

Please note that this report is largely based on primary data obtained by the engineers and academics in the USEPA's contractor group that supported the development of this report, including observations made during visits to numerous C&D processing facilities and conversations with facility owners, operators, and other members of the C&D recovery industry. All photographs presented in this report, unless stated otherwise, were taken by the USEPA's contractor and were obtained with the permission of site owners.

The development of this report also entailed collecting and analyzing secondary data. The appropriateness of the data and their intended use were assessed based on the source, collection timeframe, and scale of the geographic area represented. Preference was given to data that have undergone peer or public review (e.g., those published in government reports and peer-reviewed journals) over data sources that typically do not receive a review (e.g., conference proceedings, trade journal articles, personal estimates). Preference was given to more recent data over older data. Data representative of a larger geographic area (e.g., U.S. average or state averages) were preferred over that representative of a smaller geographic area (e.g., cities, counties). While not representative of the whole industry, to better understand the economic factors associated with the recovery of C&D, this report presents some cost data obtained via verbal communication with members of the C&D management industry. The sources of all the data used and any identified limitations are presented in the report.

2. C&D PROCESSING FACILITIES AND MATERIAL END USES

> The composition and physical characteristics of a given C&D stream depend on the source of the material (e.g., wood-frame home, concrete building, asphalt pavement) and the type of project that produces the C&D (e.g., construction, demolition, renovation).

C&D recovery is a multistep process that generally includes material segregation (i.e., isolation of the material from other C&D constituents), processing (e.g., size reduction, unwanted substance removal), and end use of the material to offset or replace virgin materials (i.e., materials in native or raw form). Some materials may go through fewer steps (wood removed through deconstruction used for a new onsite building) or additional steps (e.g., ferrous metals purchased by scrap metal brokers before end use at a steel mill). However, the recovery process for a given C&D stream or material is dependent on its characteristics and available recovered material markets.

Some C&D projects produce a highly heterogeneous C&D material stream that is composed of various components, while others generate a relatively homogeneous stream dominated by a specific material component (e.g., roofing shingles from a re-roofing job, concrete from the demolition of a bridge). Mixed C&D streams require more intensive sorting than more homogenous streams, and as C&D characteristics vary, different types of processing facilities are used. Depending on the source and composition of the debris, desired quality, and target end markets for the product, multiple approaches are employed to process C&D mechanically.

This section describes the practices currently used in the United States for most C&D recovery. Some materials, such as asphalt pavement and concrete from road and bridge work, are generated as predominantly uniform materials and transferred to a dedicated processing or reuse market. Materials may be captured for recovery from end-of-life buildings either through deconstruction, traditional demolition with onsite sorting, or traditional demolition with the mixed debris sent to a processing facility (materials separation strategies are reviewed in Section 2.1). Similarly, construction debris may be sorted at the site or processed for materials recovery at the centralized sorting facility. In most cases, mixed C&D is first transported to a processing facility where materials are separated as needed, and target materials are then processed to produce the desired product for recovery. Section 2.2 provides an overview of different types of C&D processing facilities commonly in use. Section 2.3 summarizes the common end markets for various materials recovered from C&D.

2.1 Material Separation Strategies

Many separation strategies are used to recover materials from projects where C&D is produced. Recovery of components at the point of generation can often result in materials with the greatest resale value (and often the most positive environmental benefit). This method of recovery is typically accomplished through deconstruction, selective separation before demolition, or separation of materials during generation at a construction or demolition site. In many cases, separation at the point of generation is not feasible, creating a mixed C&D stream. However, even the traditional demolition practices that produce a mixed C&D stream, as discussed in this section, generally include a "soft stripping" phase where high-value materials are removed before demolition.

2.1.1 Deconstruction

Deconstruction is "the selective dismantling or removal of materials from buildings before, or instead of, demolition" (California EPA, 2001). Deconstruction typically requires additional manual labor and less mechanical labor than traditional demolition, as a significant component of the process is the manual dismantling of individual building components (National Association of Homebuilders [NAHB], 2000). One of the main objectives of deconstruction is to minimize damage to the recovered material, increasing its quality. Deconstruction essentially reverses the construction process by removing material in the opposite order from which it was installed.

Typically, deconstruction occurs in five stages (California EPA, 2001). The first is the removal of trim work (e.g., moldings, door casings). The second is removing appliances, plumbing, windows, cabinets, and doors. The third consists of removing flooring, wall coverings, insulation, wiring, and less accessible plumbing. The fourth involves disassembling the roof. The final stage is to remove the walls, frame, and flooring support structure starting at the top of the building and progressing downward. Deconstruction involving all five stages is known as "structural" deconstruction (NAHB, 2000).

> Buildings can be designed to support repair, adaptation, deconstruction, reuse, and recycling. Key principles of designing for deconstruction were outlined by Guy & Ciarimboli, 2007. Additional work on designing buildings to reduce waste has been developed through EPA grants and publications, (USEPA, n.d.; USEPA, 2008.) Further, designing buildings to reduce waste and support reuse and recycling has been adopted by green building rating systems and credits (Lifecycle Building Challenge, n.d.).

Partial deconstruction is sometimes used to capture some of the valuable materials, followed by traditional demolition techniques for the main structure of the building (Coelho & de Brito, 2011). Stopping at the end of stage two (i.e., removing trim work and appliances, plumbing, windows, doors, and cabinets) is known as "soft stripping" (California

EPA, 2001) and is often employed in traditional demolition (Coelho & de Brito, 2011). It is also common to deconstruct certain assemblies (e.g., floor joists) that contain highly valuable materials (NAHB, 2000).

NAHB (2000) identified four criteria that indicate good deconstruction opportunities. Wood-frame homes may contain heavy timber or rare wood species that are regarded as valuable in the reuse market. Hardwood floors, antique electrical and plumbing fixtures, multipane windows, and architectural molding retain high resale value when captured during deconstruction. Homes built with high-quality bricks and low-quality mortars are good sources of easily-recoverable quality bricks. Finally, structurally sound homes are good candidates because they are less likely to contain rotten or decayed materials. The USEPA has produced a tool to help decision-makers assess a building′s suitability for deconstruction, known as the Deconstruction Rapid Assessment Tool. This tool helps the user compare the value of deconstruction against the challenges presented at a given site (USEPA, 2015c).

Proponents argue that there are environmental, social, and economic advantages to deconstruction (Dantata et al., 2005; Denhart, 2009, 2010). The environmental benefits of deconstruction are well understood: it displaces virgin material production, sequesters carbon in wood products, and reduces C&D in landfills (Denhart, 2010; Guy and McLendon, 2000; NAHB, 1997; Thomark, 2001). The greatest environmental benefit results from the higher material reuse and recycling rates, which significantly reduce the impacts of building end-of-life management and new construction (Thomark, 2001).

Researchers have also identified social benefits to deconstruction. A study of post-Katrina New Orleans found that a benefit of introducing a more hands-on demolition process was greater resident participation (Denhart, 2009). Deconstruction also facilitates preservation of historically and personally significant parts of buildings, especially after a disaster (Denhart, 2009). Also, the NAHB (2000) and other published studies (California EPA, 2001, Dantata et al., 2005) argue that deconstruction can provide a large number of jobs due to the manpower required for the process. Deconstruction does not require as much staging space as mechanized demolition, which can be helpful in dense urban environments (Dantata et al., 2005).

The economic feasibility of deconstruction depends on the circumstances of the project. A literature review of the economic impacts of deconstruction (Denhart, 2010) identified a broad range of deconstruction cost estimates, from $2 per square foot (Guy and McLendon, 2000) to $16 per square foot (Dantata et al., 2005). Deconstruction economic viability in a given locality depends on the value of the recovered material and the cost of the labor required.

In most deconstruction literature, reuse of material is discussed as a distinct concept from recovery. Reuse is cited as a process in which the material is repurposed as the same quality and type of product. Recycling, on the other hand, is referred to as a process in which the material quality is degraded, and the recovered product is then either directly reused as a lower quality material or processed to create a different product (Thomark, 2001). Whether materials from building deconstruction are reused, recycled, or disposed of depends on the material, its condition, and the availability of local markets. A list of commonly reused and recycled materials was developed by the U.S. Army Corps of Engineers (2005) and is presented in Table 2-1.

Table 2-1. Typical Materials for Reuse or Recycling from Building Deconstruction Projects (U.S. Army Corps of Engineers, 2005)

Reuse		Recycling	
▪ heavy timbers ▪ large dimensional lumber (2x6 and greater) ▪ structural metals ▪ bricks ▪ wood paneling molding and trim ▪ hardwood flooring ▪ siding	▪ cabinets ▪ electrical fixtures ▪ brass plumbing fixtures ▪ windows and doors ▪ heating ducts ▪ "architectural antiques"	▪ dimensional lumber (2x4 or smaller) ▪ drywall ▪ carpeting ▪ structural concrete and rebar ▪ bricks ▪ roofing ▪ insulation	▪ ceiling tile ▪ glass ▪ fluorescent tubes ▪ scrap metal ▪ electrical cable ▪ copper and metal pipe

Deconstruction is still an emerging field that is often considered under-studied, and therefore limited information on the subject is available in peer-reviewed journals (Denhart, 2010). This lack of data is both caused by and contributes to, a lack of application of deconstruction in the demolition field. Full-scale deconstruction accounts for a small fraction of total building removal projects in the United States, but several organizations have produced documents and tools encouraging its adoption and the incorporation of salvaged materials into new construction, including an Introduction to Deconstruction: A Comprehensive Training Workbook by the Building Materials Reuse Association, resources developed by the USDA Forest Products Laboratory, Delta Institute (2012), Public Architecture (2010), NAHB (2001), and the previously-mentioned USEPA Deconstruction Rapid Assessment Tool (USEPA, 2015c). Additionally, the City of Portland, OR is in the process of implementing deconstruction requirements in the residential sector which may highlight some best practices and lessons learned (City of Portland, 2017a).

2.1.2 Onsite C&D Segregation and Recycling

Separating high-value building materials is a fundamental component of deconstruction and is also a common practice for many regular demolition jobs. Keeping materials separated allows some materials to be transported directly to a recovery market or a more refined recovery operation such as a concrete crushing operation (University of Michigan, n.d.). Jobsite separation may also reduce disposal costs (KCSWD, 2010) as separated materials may result in a lower tipping fee. Other benefits include the ability to keep materials in the local economy (and possibly even at the same site), reducing the impact of materials transportation, and providing jobs in the local recovery and reuse industries.

> Separating the individual components of C&D at the project site where they are produced helps maximize the market value of the recovered materials and minimizes the cost and effort of downstream processing.

Demolition contractors frequently separate materials at the job site for economic reasons. The tipping fees associated with mixed C&D processing facilities or C&D landfills are often much greater than those related to material-specific processing facilities such as concrete crushing and recycling operations (CalRecycle, n.d.). Depending on the region and the availability of local aggregates, some concrete recycling operations will accept materials free of charge. In some cases, if the resulting aggregate product meets material strength requirements, clean concrete will be processed and used at the site to provide a structural component for the foundation of a new construction project. Because of the magnitude of materials that must be managed, contractors of large demolition projects will commonly employ some degree of separation of C&D material on the job site to minimize project expenses.

Separation of C&D during construction projects tends to be more challenging; materials management costs are a much smaller proportion of the cost associated with a construction project relative to a demolition project (CalRecycle, 1997). Jobsite separation involves using multiple containers and staging areas to separate scrap materials at a construction site. Several resource guides provide best management practices for job site separation of C&D (USEPA, 2015a); they include guidance in container staging and sizing, appropriate signage, and construction crew education. The challenges of job site separation include additional expenses for having multiple containers for different material types, additional labor costs for separating materials, space constraints in dense urban areas, and additional coordination of contractors and subcontractors to ensure materials separation across all stages of the project.

Another factor impeding job site separation is a lack of material-specific recovery facilities. The existence of facilities for recovery of specific components, such as non-asbestos asphalt shingles, concrete, wood, and drywall, is very region specific (these facilities are discussed in greater detail in Section 2.2). One approach that has been tried in some areas of the United States is to separate and then reuse clean segregated construction materials at the construction site itself (USEPA, 2015a). This approach includes crushing concrete and brick and using them as a base layer under concrete driveways, grinding wood for mulch or erosion control media, and pulverizing drywall as a soil supplement (CalRecycle, n.d.).

While many construction contractors avoid extensive job site separation because of the added effort, space, and cost, the U.S. Green Building Council′s LEED green building certification program has promoted this practice (discussed in detail in Chapter 4) (Hinkley Center, n.d.). Diverting a fraction of the material can provide credit toward achieving certification, and onsite separation increases the likelihood that a project can achieve the diversion goal.

2.1.3 Mixed C&D

Numerous types of processing facilities sometimes referred to as materials recovery facilities (MRF), are used to recycle C&D. Most C&D recovered in the United States is managed at one of these facilities. Some facilities focus on a specific type of material (e.g., concrete, wood, drywall), while others focus on mixed C&D. Mixed C&D MRFs use some combination of equipment and manual labor to separate materials into components. These materials may be processed onsite or sent on to a more specialized facility. Material targets and recovery rates vary widely depending on the recovery facility and properties of the material stream. Section 2.2 describes the different types of C&D processing facilities operating in the United States.

2.2 C&D Material Processing Facilities

C&D collected and sent for recovery is typically first processed at a mixed C&D processing facility or a material-specific processing facility, depending on whether the materials were already segregated at the point of origin. Specific components of C&D that are separated from mixed loads at a mixed C&D processing facility may be sent to material-specific processing facilities. The various types of C&D processing facilities are summarized below.

2.2.1 Mixed C&D Facilities

Mixed C&D facilities accept heterogeneous loads of material. Mixed loads are commonly produced by construction, renovation, and smaller demolition projects. Before producing marketable end products for recycling, target materials are separated. Given the additional processing effort, these facilities generally will charge a higher tipping fee than a facility accepting only presorted material. As discussed in detail in Section 3.1.5, the average nationwide tipping fee for mixed C&D MRFs appears higher than the average nationwide tipping fee at C&D landfills (C&D MRFs are more common in areas where landfill tipping fees are already high). A photograph of a mixed C&D MRF tipping floor is presented in Figure 2-1.

Figure 2-1. Mixed C&D MRFs Separate C&D into Individual Material Types for Recovery

Configurations of mixed C&D facilities range from simple manual to highly automated processing, and the types and quality of materials recovered depend on the equipment and strategies employed at each MRF. More mechanized facilities achieve greater throughput by combining mechanical and manual processes with lower labor costs, although at greater capital cost and energy use. The simplest facilities use laborers and equipment to pick through and manually sort C&D, as illustrated in Figure 2-2. This approach is often referred to as the "dump and pick" approach, and typically only the most valuable materials are recovered for reuse or recycling. These operations can occur at the tipping face of the landfill or a sorting facility such as a transfer station.

Figure 2-2. Flow Diagram of a Typical Operation Where Mixed C&D is Unloaded and Sorted Manually

C&D processing facilities (and particularly mixed C&D MRFs) can use a positive sorting process, a negative sorting process, or some combination of the two. A positive sorting process involves the removal of desired materials for recovery, while negative sorting removes unwanted materials for disposal (or additional processing). For the same stream of material, a positive sorting process would be expected to produce a higher-quality, lower-volume stream of recovered material.

Facilities will often combine manual processes with mechanical equipment to separate target materials, as illustrated in Figures 2-3 and 2-4. In the United States, depending on specific state public policy directives, these facilities are commonly regulated as permitted solid waste management facilities and must comply with requirements such as stockpile size, offsite emission control, and recordkeeping; these requirements may be less stringent or different at another facility processing only exempted materials, as will be discussed in Section 3.2.2. Incoming loads of C&D must meet certain criteria (e.g., only C&D may be allowed); loads are inspected as necessary to ensure that only appropriate materials are processed. The operator charges a tipping fee based on the type of material and either the weight or volume of the container or vehicle.

Loads of C&D are tipped in a designated area, followed by a visual inspection and removal of unwanted materials. Some operators conduct a preliminary size reduction step with an excavator or similar equipment before moving the material to the mechanized process train. The first step in the mechanized separation process is mechanical screening. In some cases, an initial screening step separates the incoming material into two size fractions (e.g., less than 12 inches and greater than 12 inches), which are then further processed (including additional screening) in a separate processing line (Figure 2-4).

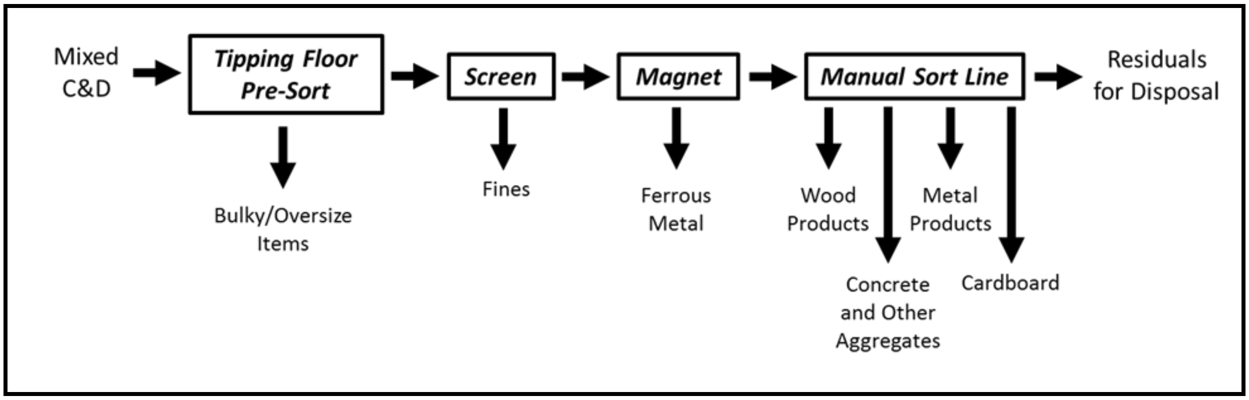


Figure 2-3. Flow Diagram of a C&D MRF Using Some Mechanical Separation, Followed by Manual Separation

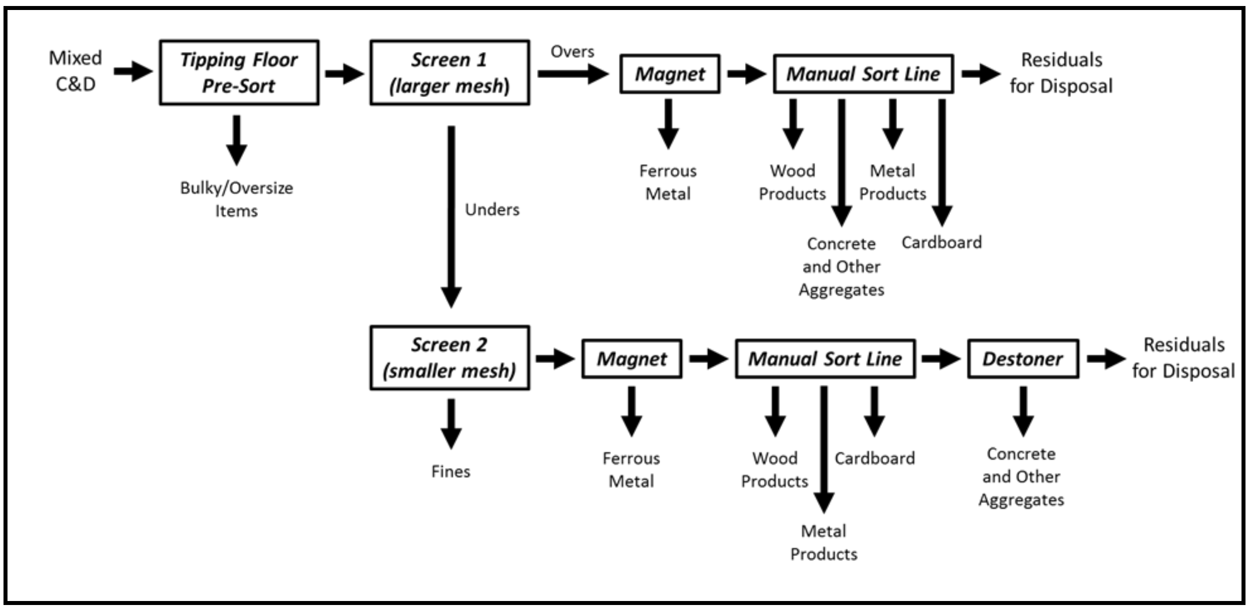


Figure 2-4. Flow Diagram of a Mixed C&D MRF Using Extensive Mechanical Processing to Separate Materials before a Manual Sort

Following an initial screening and magnet separation, the materials proceed via conveyor along a picking line. Workers stationed on each side of the conveyor manually remove target materials and place them into designated bins (i.e., positive sorting). Later, the materials are removed and placed in designated storage or processing areas. The photo in Figure 2-5 depicts a typical picking line operation; workers should be adequately trained and provided with necessary safety gear (e.g., eye protection, breathing masks, gloves). Target materials for manual removal include wood, smaller pieces of concrete and masonry, metals, and plastics (e.g., 5-gallon buckets). Figure 2-6 shows the use of an inclined vibratory screen for initial screening to separate the C&D for further processing on two different processing lines. Throughout the process, magnets remove ferrous metals (Figure 2-7). Magnet configurations include overhead magnets and pulley magnets.

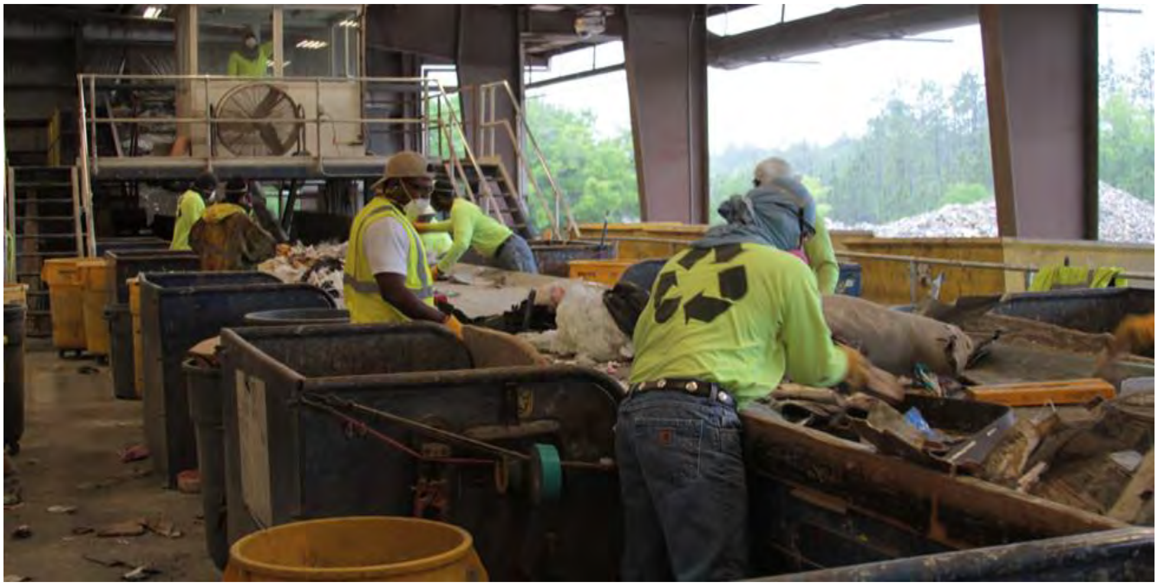


Figure 2-5. C&D Recovery Facilities Rely on a Combination of Manual and Mechanical Separation to Produce a Variety of Clean and Marketable Materials

Figure 2-6. Screens Are Used to Separate Materials Based on Their Size

Figure 2-7. Magnets Are Used to Remove Steel and Other Ferrous Metal

Depending on the facility, the materials that pass through the manual sort line may be managed as residual and disposed of (typically at a local municipal landfill), or additional mechanical processing steps are employed to further separate and recover materials. Equipment that separates materials based on density is common. Some facilities use float tanks where wood is removed from the surface of the water, and concrete pieces or other aggregates are retrieved from the bottom of the tank. More common in modern facilities are air classifiers such as destoners that separate lighter from denser materials (Figure 2-8).

The use of optical sorters is also becoming more common in C&D sorting. Optical sorters collect molecular-level information about materials using a light-emitting source, lenses, spectrometers, cameras, and shutter valves. During sorting, the material is sent through the sorter at high speed under a spectrum of wavelengths. A spectrometer identifies the material, and a shutter valve passes it into the correct chute of the conveyor. Optical sorters would not be able to identify (and sort out) harmful materials (e.g., lead-based paint); however, additional automated detection technologies (e.g., x-ray fluorescence, laser-induced breakdown spectroscopy) have the potential to identify certain harmful materials based on their chemical makeup.

Figure 2-8. Air Classifiers, or Destoners, Separate Heavy and Light Materials

Some mixed C&D processing facilities may have additional material-specific processing steps (e.g., concrete crushing, wood grinding), which may allow recovered materials to be sold directly to their end markets rather than requiring them to be sent to separate facilities for additional processing. For example, recycled concrete aggregate may be sold to contractors for use as a construction fill, or the recovered wood fraction that was in the facility may be size reduced with a grinder or horizontal mill to be sold to landscapers for use as mulch. Other mixed C&D processing facilities may transfer recovered materials to material-specific processing facilities.

2.2.2 Aggregate Processing Facilities

Aggregate processing facilities primarily accept and handle demolished Portland cement concrete (PCC) products, but may also accept and process brick and masonry, asphalt pavement, and other similar aggregate materials. PCC is different from asphalt concrete, which primarily uses asphalt as a binding material, whereas PCC uses Portland cement as a binder in addition to other additives such as fly ash (FHWA, 1998).

Both portable and stationary processing operations are integral to the PCC recovery industry in the United States (CDRA, 2012). Individual demolition sites that primarily generate large amounts of PCC may contract a mobile operation to crush and produce aggregate onsite. Some mixed C&D processing facilities stockpile recovered PCC and periodically hire a portable crusher contractor to bring in and operate a mobile crusher. Dedicated PCC processing operations generally use fixed equipment.

Size reduction to produce marketable-sized products is the primary objective of an aggregate processing facility. Typical size reduction equipment includes jaw crushers, impact crushers, and cone crushers. In most cases, multiple crushers are used. Unlike mixed C&D facilities, aggregate processing facilities commonly track material quantities by volume instead of by mass. In some cases, a tipping fee may be levied for the receipt of materials, but in regions where the market value of recycled concrete products is sufficiently high, materials may be accepted at no charge.

Aggregate processing facilities vary in size and configuration, but typically follow a similar series of steps. When material arrives at an aggregate processing facility, the container or vehicle is inspected and directed to an appropriate unloading location. Materials may be stored for weeks before processing. Large pieces of PCC may first need to be size reduced using mobile equipment such as excavators equipped with an appropriate attachment. Excavators, loaders, and other heavy equipment are used to transport unprocessed material to the beginning of the process train and, as necessary, remove non-aggregate materials.

Figure 2-9 shows the material flow through a conventional aggregate processing facility. A preliminary screening step may be used to remove fine materials. The first size reduction step is a primary crusher (as shown in Figure 2-10), which in most cases will be a jaw or impact crusher. After primary crushing, the material is passed under a magnet to extract ferrous metals (e.g., steel reinforcing bar); additional overhead and pulley magnets may be used in subsequent stages of the crushing process. After primary crushing, the materials move via conveyor to a secondary crusher (commonly a cone crusher). The material then passes through vibratory screens to extract desired size materials and, as needed, materials are conveyed to the secondary crusher again to produce the product you want. Some aggregate processors also utilize tertiary crushing, depending on the setup of the facility. Aggregate processing facilities may use separate crushers and reclaimed asphalt pavement (RAP)-breakers for processing non-concrete materials such as RAP or larger asphalt pavement materials.

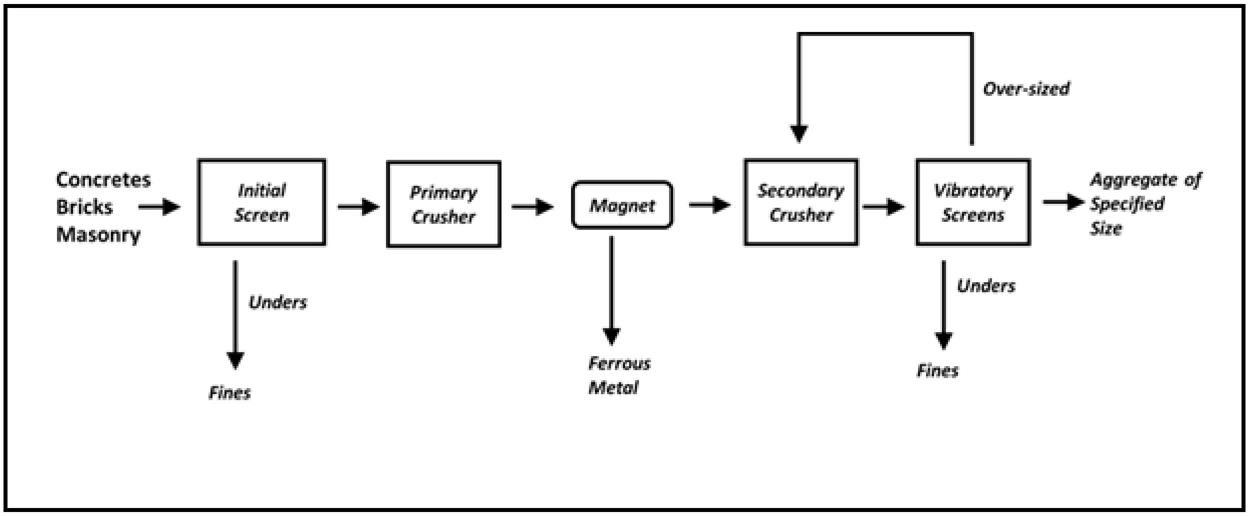


Figure 2-9. Flow Diagram for a Typical Aggregate Processing Facility Producing Crushed Aggregates from C&D

Figure 2-10. PCC Is Processed by Crushing, Removing Metal, and Screening to the Desired Gradation

2.2.3 Non-Asbestos Asphalt Shingle Processing Facilities

Non-asbestos asphalt shingles that are segregated for recovery (by the roofing contractor) are often managed at stand-alone recovery facilities, though in some cases mixed C&D MRFs may periodically contract with mobile shingle processing companies to size-reduce shingles for desired end markets (Figure 2-11). Figure 2-12 presents a process flow diagram for a non-asbestos asphalt shingle processing facility. During the first processing step, unwanted materials (e.g., roofing paper, wood pieces) are removed from the load, and the material is passed through a grinder for size reduction. A magnet extracts nails from the ground material before screening. Screening then allows the facility to obtain the desired size of end products to meet local market demand.

Figure 2-11. Mobile Grinder Used for Processing Non-Asbestos Asphalt Shingles

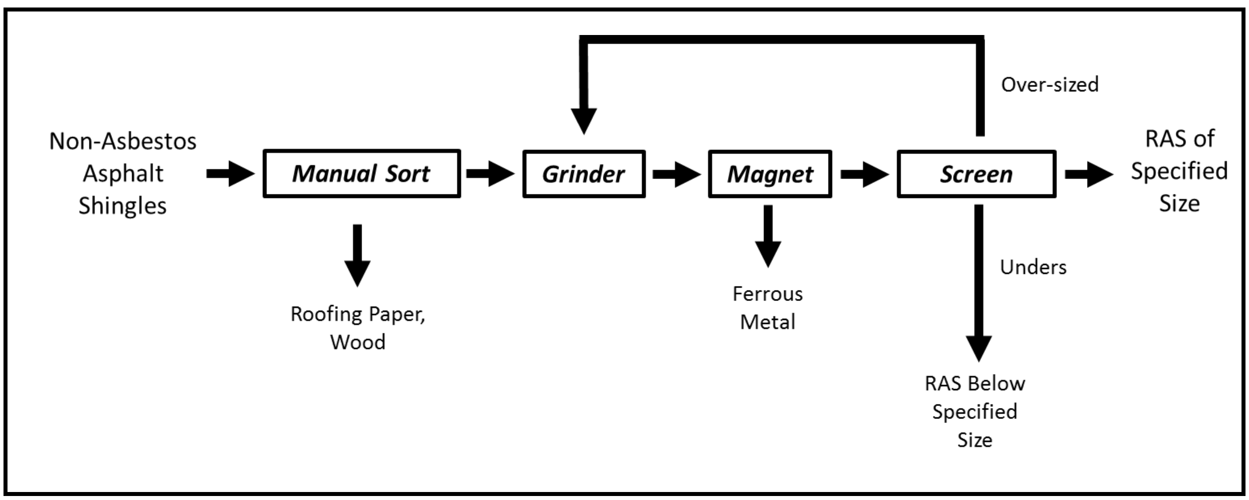


Figure 2-12. Flow Diagram for a Typical Asphalt Shingles Recovery Facility That Processes Segregated Non-Asbestos Asphalt Shingles Materials into Recycled Asphalt Shingles (RAS)

2.2.4 Asphalt Pavement Recovery

Except for large chunks of asphalt pavement recovered from the demolition of parking lots and other small pavement areas, most RAP is not handled at C&D processing facilities; as-generated RAP from road resurfacing work has historically either been sent directly to asphalt plants and incorporated into new pavement mixes (providing a substitute for virgin asphalt and aggregate on a 1-to-1 basis) or recycled in place. On a national average basis, 20% of the total 2014 asphalt pavement mix (NAPA, 2015) consisted of RAP (by mass). RAP is commonly produced through cold milling from asphalt roads that have reached the end of their usable life, as presented in Figure 2-13.

Figure 2-13. Existing Asphalt Roads Are Milled and Incorporated into New Asphalt Pavement

RAP recycling methods can be classified into offsite and in-place (i.e., onsite) recycling. Offsite recycling of RAP involves the transport of the material to asphalt mix plants for inclusion in new asphalt pavement production. As of 2014, most asphalt pavement mix was produced at hot mix asphalt (HMA) plants (representing approximately two-thirds of all asphalt pavement) and warm mix asphalt (WMA) plants (producing most of the remaining pavement) (NAPA, 2015). A process flow schematic for RAP recycling at an HMA plant is presented in Figure 2-14.

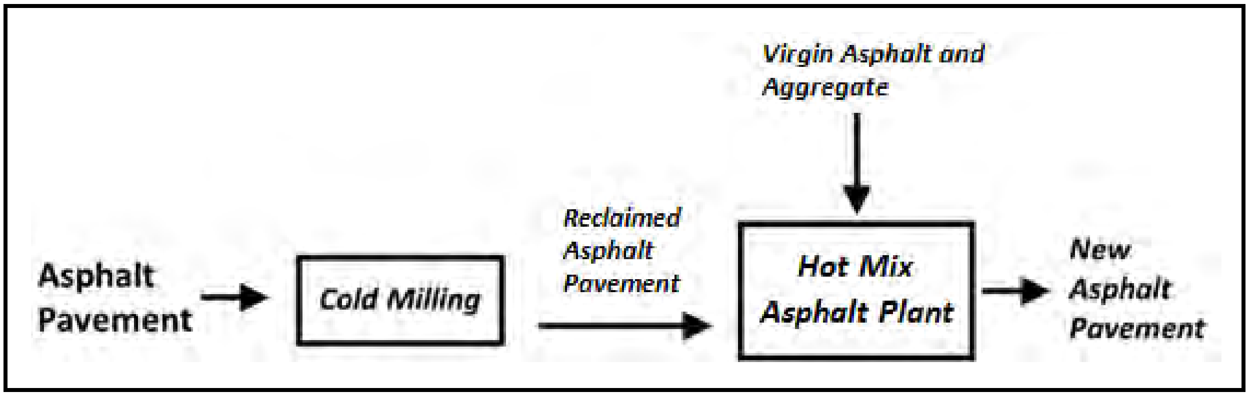


Figure 2-14. Flow Diagram for RAP Recycling at an HMA Plant

In-place recycling involves pavement removal, reconditioning, and reapplication by equipment in single or in multiple passes. The Federal Highway Administration (FHWA, 1997) describes in-place asphalt pavement recycling techniques including hot in-place recycling, cold in-place recycling, and full depth reclamation methods. In hot in-place recycling, asphalt pavement is heated to soften the material and is then removed and mixed with virgin asphalt and aggregate before being reapplied. Cold in-place recycling is similar, but does not preheat the pavement; once the pavement is removed, a recycling agent or emulsion is used to keep the asphalt workable until the mix is placed and compacted. The full depth reclamation process involves reclaiming the existing in-place asphalt pavement as well as a portion of the underlying base course, which are both removed and treated with additives to improve stability before being reapplied as a new base course. This is accomplished by using heavy equipment such as a mill or scarifier to remove material; then the material is pulverized or milled to create a new aggregate that is mixed with an additive and then reapplied.

2.2.5 Wood Processing Facilities

Most wood in the C&D stream is commingled with other building components and must be separated at mixed C&D processing facilities using manual and mechanical techniques. Nonetheless, while most recovered wood will be separated at mixed C&D processing facilities, some amount will be processed at facilities that focus primarily on wood as a recovered material. These wood processing facilities typically accept wood from yard waste, land clearing, wood product manufacture, and C&D activities. Depending on the market, different wood sources can be processed separately. With C&D wood and land clearing debris (LCD),[1] the major end uses (boiler fuel or mulch) are the same, and some facilities will accept and process them at the same time.

During processing, the first step is to remove (frequently by hand) unwanted materials and then send the remaining fraction through a wood grinder. The ground material then may pass through a screen to remove wood fines (similar in appearance to sawdust). The remains from the screen are conveyed under a magnet to extract any ferrous materials such as screws, hinges, and nails. Larger wood chips can be used as a boiler fuel and the clean lumber is often used to produce mulch. Figure 2-15 shows the process at a typical wood processing facility.

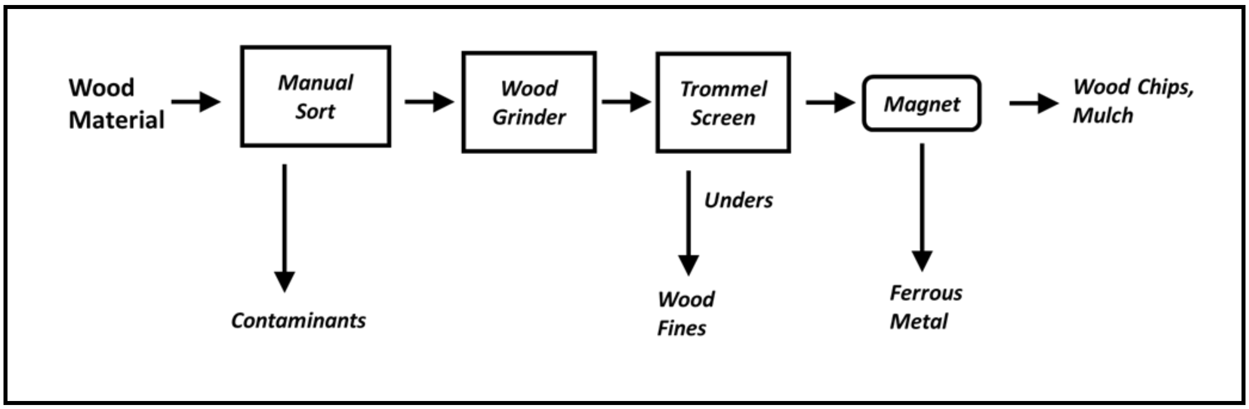


Figure 2-15. Flow Diagram of a Typical Wood Processing Facility

2.2.6 Drywall Recovery Facilities

Several facilities in the United States process only drywall from construction sites. Figure 2-16 shows an example of a normal drywall recovery facility process. The recovery operation primarily involves removing the paper from the drywall followed by size reduction suitable to market demand. Tub grinders or horizontal mills are most commonly used to reduce the size of drywall. A dust suppression or collection system is needed as part of this operation. The size-reduced drywall is then passed through a screen to separate any remaining paper from the rest of the material. Drywall recovery facilities produce powdered gypsum that has been marketed to new drywall manufacturing operations and agricultural consumers, where such use of recycled drywall gypsum in agricultural applications has been approved by state and local governments. In some cases, the drywall recycler may further

[1] LCD consists primarily of the vegetation, soil, and rock resulting from preparing a site for construction. Much of the soil and rock may remain onsite and be incorporated into the desired site grades, but excess materials may be transported offsite for processing or recycling.

process the gypsum (e.g., pelletize the gypsum) to create value-added agricultural products (e.g., bagged gypsum pellets). If markets exist, the paper may be recovered as well.

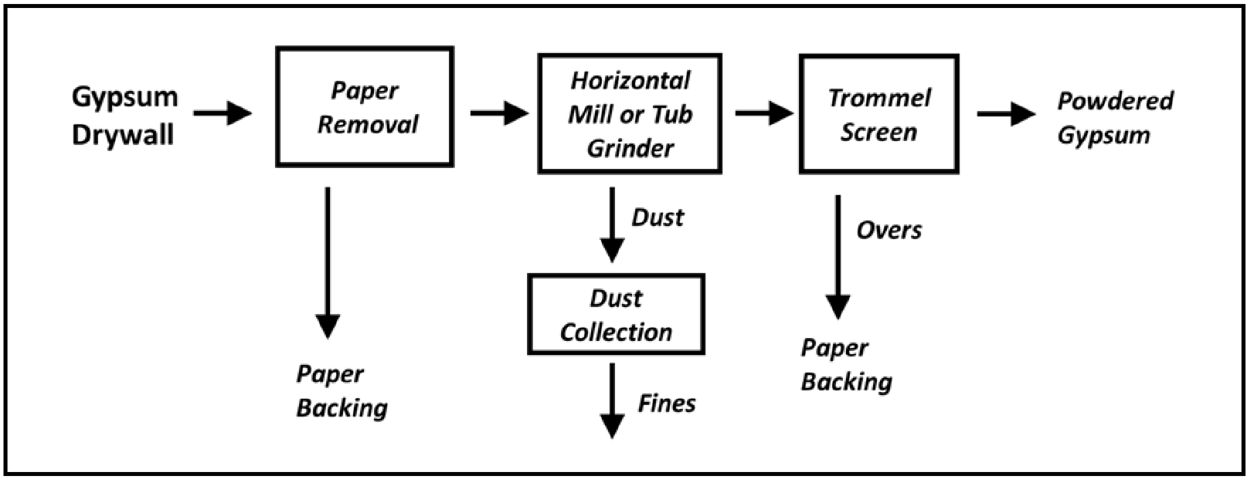


Figure 2-16. Flow Diagram for a Typical Drywall Recovery Facility That Receives Segregated Drywall and Produces Gypsum Powder

2.3 Material-Specific End Uses

As discussed in Section 1, C&D is a diverse material stream, with the major components including PCC, asphalt pavement, wood, LCD, non-asbestos asphalt shingles, drywall, and metals. This section discusses the traditional end uses for each material. For any of these uses, it is important to ensure the use is conducted in a manner that protects human health and the environment.

2.3.1 Portland Cement Concrete

PCC represents the largest single material class encountered in C&D (USEPA, 2016a). PCC is used for building foundations, structural building components, roads, bridges, and various miscellaneous structures. PCC mixes consist primarily of coarse and fine aggregate, Portland cement alone or blended with other supplementary cementitious materials, and water. PCC is manufactured at concrete batch plants, where the aggregate, cement, and water are mixed with minor amounts of required admixtures (e.g., accelerators, superplasticizers) to meet an engineered product design (Nisbet et al., 2002). The PCC is shipped to the construction site using mixing trucks or used directly to manufacture precast concrete products such as blocks and pipes.

When PCC is poured in place as part of a construction project, a small amount of the concrete may remain in the mixing truck. This material is often discharged back at the concrete batch plant, but at some construction sites it might be discharged, allowed to harden, and eventually added to the mixed C&D. While the relative contribution from poured PCC to construction debris is small, PCC in the form of the concrete block may represent a larger fraction of the debris at building sites using the block as a framing material. Most PCC in C&D results from the demolition of large concrete buildings, roads, bridges, and other infrastructure, and because PCC is often the dominant material from these projects, contractors normally manage this material separately from mixed C&D.

The primary end market for crushed PCC has been a replacement for construction stone used in road and building construction. Examples include aggregate materials in size range of 3 inches to 1-1/2 inches, 1-1/2 inches to ¾ inches, 3/8 inches minus or pea gravel, 3/4 inches drain rock and utility sand. In cases where the products meet the specifications of a state transportation department or a local public works department, the products may be marketed specifically by the name of the specified product.

In many states, the department of transportation provides specifications for the use of crushed concrete in road base or similar applications. The use of crushed PCC as an aggregate in new PCC or new asphalt pavement has been explored, but the lack of established specifications has limited this practice in the United States. Other recovered uses of PCC include riprap for erosion control, clean fill material, and artificial reefs.

2.3.2 Masonry Products

Masonry products include a wide variety of building materials such as brick, block, stone, and tile. Masonry products are typically held together by a mortar or joint compound that is usually processed along with the primary material. In most C&D recovery operations, masonry products are commonly classified into the same aggregate sizes and stockpiles as processed PCC, although crushed concrete products containing too much foreign material may not command as high a price. Some facilities that receive source-segregated loads of brick have marketed the crushed end product to landscapers for application as an ornamental stone. Recovery of whole masonry product and subsequent use in building applications has been reported for some materials, primarily clay brick.

2.3.3 Asphalt Shingles

Asphalt shingles consist of an asphalt-impregnated mat, with the bottom coated with a fine mineral surface and the top coated with a coarser mineral fraction. The coarse minerals are colored to meet the desired product appearance. The asphalt content of an asphalt shingle is 19% to 36% by weight (USEPA, 2015d).

The lifespan of an asphalt shingle roof depends on the quality of the shingle product and the environmental exposure conditions, but a common replacement period for shingle roofs is approximately 20 years (NCHRP, 2013). Upon re-roofing, the old shingles are typically removed (along with the roofing felt and other materials, as required) and replaced with new materials. In some cases, new asphalt shingles will be placed on top of the older shingles. Re-roofing projects produce a relatively large amount of uniform material over a short time.

Size-reduced and screened recycled asphalt shingles (RAS) are commonly marketed as feedstock in the manufacture of HMA, where asphalt in the ground shingles offsets the consumption of virgin asphalt. NAPA (2015) estimates that nearly 2 million tons of asphalt shingles were recycled into asphalt pavement in 2014; on average, asphalt shingles represented approximately 0.5% to 1.5% of pavement mixes.

Minor markets for ground non-asbestos asphalt shingles include pothole patch and surfacing material for unpaved roads. Non-asbestos asphalt shingles have a relatively high BTU value and thus have the potential to be combusted for energy in waste-to-energy facilities or industrial facilities such as cement kilns. However, these practices are not common in the United States. Landfill operators will often stockpile dedicated loads of shingles for later use in landfill road construction, especially for wet weather conditions.

2.3.4 Asphalt Pavement

Asphalt pavement also referred to as asphalt concrete or bituminous concrete, is heavily employed in the United States as a paving layer in roadways and parking lots. Asphalt pavement consists of a mixture of coarse and fine aggregate (approximately 95% by mass) and asphalt cement or bitumen (roughly 5% by mass). Asphalt pavement is typically produced in hot mix asphalt plants, which may consist of drum or batch mix plants where the aggregate, bitumen, and in many cases recycled materials (predominantly RAP) are blended to meet an engineering mix design. The mix is then hauled by truck to the construction site where the pavement is compacted in place.

Most RAP is entering the C&D stream from milling existing asphalt pavement as part of road resurfacing. However, some milled asphalt pavement is recycled in place, as described in Section 2.2.4. Due to the nature of the in-place recycling process, it does not appear that there are any estimates of the nationwide quantity of in-place recycled RAP.

In some cases, asphalt pavement is demolished using heavy equipment, resulting in much larger pieces. While some of this debris might be transported to an asphalt pavement production facility for additional processing, in many cases pavement in this form is sent to a mixed debris processing facility or an aggregate recycling facility.

Asphalt pavement is frequently recycled in the United States. In 2013, 67.8 million tons of RAP were recycled, corresponding to a recycling rate of over 99% (NAPA, 2014). Smaller amounts of asphalt pavement are recycled as construction aggregate.

2.3.5 Wood and Land-Clearing Debris

Wood products are heavily used in building construction in the United States, as well as for outdoor structural applications (fences, decks, utility poles). Wood products take numerous forms, including dimensional lumber, engineered wood (e.g., plywood, oriented strand board), and poles. Depending on end use, some wood products may be treated with chemicals to delay natural decay. Wood products enter the C&D stream both as scrap from new construction and from the demolition of in-service wood structures.

Under certain scenarios (e.g., see Section 2.1.1), wood components may be targeted for select removal from a building and eventual reuse in another structural or architectural application. In most cases, however, the markets for recovered wood products from C&D have not been for building or structural purposes. One of the largest markets for recovered wood has been as a fuel source for industrial boilers or other energy production facilities. In recent years, a growing number of facilities have been constructed to convert biomass to energy, and C&D wood represents a large potential feedstock for this market. C&D wood in many locations is used to create a landscape mulch product (Figure 2-17), particularly after the addition of a coloring agent to increase visual appeal. Smaller end uses for C&D wood have been reported, ranging from high-value utilized in the manufacture of new engineered wood products (e.g., oriented strand board, fiberboard, particle boards) to lower-value uses such as a compost feedstock, animal bedding, and erosion control material. Fines from wood or LCD processing may serve as a fill material, but the potential for the reuse of fines in this application depends on the quality of the incoming material stream.

Identified challenges associated with creating a C&D wood product of sufficient quality revolve around minimizing impurities, including factors that affect heating value (moisture, soil content) and those that pose environmental concerns (e.g., lead from painted wood, arsenic from treated wood).

Figure 2-17. Mulch and Wood Chips Can Be Produced from C&D Wood Using a Grinder or Mill

2.3.6 Drywall

In the United States, drywall (also referred to wallboard or plasterboard) is a major interior wall material in residential and commercial buildings. Drywall consists of a gypsum core covered on each side with a paper backing; Gypsum contributes over 90% of the weight of the drywall product. During the construction process, drywall sheets are fixed to the internal framing of a building with nails, and the joints and nail locations are then covered with a joint compound and sanded to form a smooth surface. Numerous vendors sell drywall products of different sizes in the United States. Some specialty drywall products are also marketed, including type X drywall (for higher fire rating) green board (for greater moisture resistance), and blue board (for plaster applications).

Drywall must be cut to meet the dimensions and openings of the building, so a relatively large percentage is wasted at construction sites compared to other materials. Because a specialized drywall contractor is scheduled to work during one specific period in the construction process, a significant amount of drywall scrap is produced during that time. In some cases, during demolition or renovation, drywall is removed and managed as a distinct material (Figure 2-18). However, in many demolition projects, drywall is not removed separately but is mixed with other debris as the structure is torn down.

Figure 2-18. Drywall Has the Potential to Be Recycled into New Drywall, as an Agricultural Amendment, or as an Ingredient in Portland Cement

Recycling markets have been developed for scrap drywall, although in many cases these markets are limited to scrap from new construction. In some areas of North America (particularly the Northwest), scrap drywall is used in the manufacture of new drywall. Drywall manufacturing facilities often recycle a small amount of their scrap into the production process, and thus they can accommodate some amount of recycled material. As gypsum is an ingredient in the manufacture of Portland cement, some cement plants have attempted to incorporate gypsum from recovered drywall. This practice has been limited in the United States because of the need for an abundant and constant supply of stable material. In areas where local and state governments allow the use of recovered gypsum from wallboard in land applications, gypsum from drywall has been used as a soil and plant amendment. Unlike lime, gypsum does not dramatically change the pH of the soil; thus, gypsum has been used in applications as a calcium where a pH increase is not desired. Some recyclers have marketed a gypsum powder resulting from crushed drywall, while others produce specialty agricultural products (e.g., gypsum pellets). Other markets for recovered drywall have included animal bedding and compost amendment.

Recovered drywall end markets often require that the gypsum is separated from the paper. This separation can be accomplished with a combination of grinders and screens. This process can be extremely dusty and appropriate dust containment is necessary. Some markets can accommodate a small amount of clean paper without deleterious effect.

2.3.7 Metals

Metal products are used in various building applications and in other structures including structural components, flashing, piping, and wiring. Metals and alloys commonly encountered in C&D include steel (including galvanized steel), cast iron, aluminum, brass, tin, lead, and copper. A small amount of metal may result as scrap during the construction process. In demolition, large buildings usually will be stripped of metal products prior to bulk demolition of the structure, or, as necessary; metals will be separated during the demolition process itself. The photograph in Figure 2-19 shows a significant amount of scrap metal from a demolition project.

Magnets for removing ferrous metal from other C&D components are present at nearly all mechanized C&D recovery facilities. The scrap metal market is well established, and C&D processing facility operators will market their metals to scrap metal recyclers or through brokers. The end use of metal from C&D is generally the production of metal precursor products (e.g., billets, ingots), where its use offsets the consumption of virgin ore.

Figure 2-19. Scrap Metal Has a Well-Established Market, Making It One of the Most Commonly Recycled C&D Materials

2.3.8 C&D Fines and Processing Residuals

Depending on the configuration of the C&D processing operation, facility operators may produce various product streams referred to by names such as fines, residuals, or screened materials (see Figure 2-20). Reuse markets for these materials may exist but depend heavily upon their physical and chemical characteristics, local market conditions, and applicable regulatory allowances.

Figure 2-20. C&D Fines are a Major Component of Mechanized C&D Recovery Operations, and Historically Have Been Used as Cover Material at Landfills

As indicated in Figures 2-3 and 2-4, mechanized processing facilities typically employ a screening step early in the operation with the intention of removing smaller components from the processed C&D stream. These screenings commonly referred to as C&D fines or recovered screened material (RSM), are generally less than 1 to 2 inches in width. Their composition is dominated by soil and similar particles but may include small pieces of wood, gypsum, asphalt pavement, glass, and plastic. The composition of C&D fines depends on the source material and the level and types of processing prior to the screening step. For example, C&D fines that originate from materials just crushed or processed in some manner will contain less soil and more waste materials.

Some operators may deliberately size reduce part of the incoming material if recovery markets are less than favorable. The objective of this step is either to reduce the volume needed for transport or to create a material that can be used as alternative daily cover (ADC) at a landfill (as discussed in more detail in Section 3.4.7). In the industry, these materials are more commonly referred to as process residuals or simply ADC, rather than fines, although definitions differ regionally.

Residuals remaining from a mixed C&D MRF (i.e., materials remaining after targeted materials have been removed) consist largely of paper, plastics, and small pieces of wood. An example of these residuals is shown in the photograph in Figure 2-21. Processing residuals and unwanted materials produced at C&D processing facilities are typically disposed of at an MSW landfill or waste-to-energy facility, but they may be recovered and marketed as refuse-derived fuel (RDF).

Figure 2-21. Much of the Remaining Material on a C&D Processing Line Has a High Caloric Value and May Be Used as a Fuel Source

2.3.9 Other Materials

Other materials that comprise a noteworthy portion of recovered C&D include cardboard and plastics. Cardboard is highly recyclable and can be retrieved during C&D sorting (Figure 2-22). At some recovery operations, plastics (e.g., plastic buckets) are targeted as a recovered material. Facilities may also target the recovery of carpet. However, a nationwide survey of C&D processing facilities suggested that only approximately 30% of mixed C&D processing facilities recover carpet and, at these facilities, carpet typically represents less than 2% (by mass) of the recovered materials (CDRA, 2015).

Figure 2-22. Cardboard Is Commonly Recovered From C&D and Recycled

3. FACTORS IMPACTING C&D RECOVERY

In this section, the different factors that affect C&D recovery are reviewed. These factors include various considerations related to the economics of different C&D management options, public policy-related topics, corporate policies (e.g., green building certifications, intracompany building deconstruction/demolition standards), and material-specific market considerations. As mentioned previously, tipping fee information presented here was gathered from publicly available information posted on C&D management facility websites, as well as through contact and discussion with facility owners, operators, and personnel (IWCS, 2016). Unless otherwise noted, state C&D management public policy information was summarized from USEPA (2015a).

Selected factors that influence C&D recovery rates include economics, material-specific market considerations and public and corporate policies.

3.1 Economics

3.1.1 Economic Decisions by the C&D Contractor

When site managers have the option of disposing of or recovering C&D, economic factors are typically the driving force behind their decisions. C&D recovery generally becomes a more attractive option in situations where recovery is more economically advantageous; however, nonmonetary incentives can also influence decision-making.

Transportation costs and the variability in tipping fees for recovery and disposal facilities play a major role in C&D end-of-life (EOL) management decision-making. For example, a demolition contractor may have to choose between hauling materials from an inner-city demolition site to a nearby C&D processing facility for a higher tipping fee, or transporting the material to a C&D landfill on the outskirts of the city for a lower tipping fee. Alternatively, depending on location, construction contractors may have the option of securing C&D roll-off containers (large open dumpsters) from local recovery companies or disposal companies; the distance between the job site and each C&D management facility (recycler or landfill) will impact the fees associated with the roll-off services of each.

Depending on the nature of the specific C&D, costs associated with site C&D removal and offsite management may be reduced as some states allow the onsite beneficial use of clean fill material.

The existence of established, local markets for specific C&D materials is another vital economic factor that influences EOL C&D management practices. For example, competition among several PCC processing facilities in an area may lower the price of recycling demolished PCC and may favor the selection of PCC recycling in that locality. C&D

contractors will typically review material markets to estimate the worth of the different materials that will be generated from the project, and then use this information to determine the most cost-effective management practice. Table 3-1 provides a summary of various economic factors and considerations that influence C&D EOL management decisions.

Table 3-1. Economic Considerations of the C&D Contractor

Economic Factor	Considerations
Jobsite Management	▪ Economics of recovery versus disposal of construction discards/scraps ▪ Economics of deconstruction versus demolition ▪ Impact on recyclability and material value of commingled versus source-segregated C&D
Transport	▪ Economics of self-haul versus retaining a C&D hauler or recovery/disposal company to provide roll-off containers ▪ Distance from the construction/demolition site to the nearest recovery/disposal facility
Tipping Fees and Onsite Use	▪ Economics of C&D disposal facility tipping fees versus C&D recovery facility tipping fees ▪ Potential savings associated with onsite recovery

3.1.2 Labor Requirements

The previous section of this report summarized C&D separation strategies used by C&D contractors. The selection of a separation method can play a role in labor requirements, which in turn may influence a contractor’s decision to pursue recovery or disposal. When discarded materials are commingled in a common container for removal from the job site, labor requirements at the job site are at their minimum. If the debris is transported to a processing facility, the labor associated with material separation is integrated into the processing facility’s tipping fee.

A processing facility’s level of automation will also directly impact its personnel requirements. A facility that solely uses manual picking requires more low-skill laborers compared to a highly-automated facility, which would require a smaller workforce with a more advanced skill set.

When a centralized processing facility is not available or economically viable, the contractor may attempt to separate desired materials at the job site. Depending on the degree to which materials are commingled, separation may require little in the way of additional labor. For example, drywall scrap at a construction site is generally produced during a specific window of time in the project’s schedule; therefore, a contractor can place segregated material in a specified container in the staging area with little or no additional effort. When activities result in naturally commingled materials (e.g., a renovation project), material separation will require additional labor.

The impact of labor is most pronounced in demolition projects where a large amount of soft-stripping or deconstruction occurs. The value of recovered materials may be much higher as they command a high-end market, but this requires more time for the manual separation of components (USEPA, n.d.). The cost of deconstructing is estimated to range from $2 to $16 per square foot, and the economies are highly dependent on the value of the recovered material and the cost of labor in the locality (Dantata et al., 2005). Local prevailing wages may influence the viability of deconstruction for a given project due to the relatively large amount of manual labor associated with deconstruction. Traditional demolition of a given structure is often quicker and generally, requires fewer workers. The lower cost of material disposal in deconstruction may offset some of the additional labor cost (Kibert and Languell, 2000). Additional information on the practice of deconstruction can be found in Section 2.1.1.

3.1.3 Hauling Distance

The distance between the job site and disposal/recovery facilities is an important economic consideration. C&D typically includes heavy or bulky materials (e.g., PCC, asphalt, bricks). Hauling fees can become costly, particularly when road weight restrictions limit the per-load quantity of C&D carried.

There are more than 1,500 C&D-specific disposal facilities in the United States (USEPA, 2012). In addition, C&D can often be disposed of at other disposal facilities (e.g., municipal solid waste [MSW] landfills, inert waste landfills, dry waste landfills). In comparison, there were only 512 C&D recovery facilities as of 2012 (USEPA, 2015a). Figure 3-1 shows the distance to the nearest C&D landfill and mixed C&D MRF. The difference between these maps indicates that there are regions of the country where reaching a C&D MRF requires hundreds of miles of additional transport.

Major costs associated with C&D transportation include fuel, driver labor, vehicle maintenance, and hauler permit/certification fees. Transportation costs can vary dramatically both regionally and over time. As of the date of the development of this report, U.S. diesel prices are relatively low; however, historically, the highest diesel prices have been on the West Coast, and Rocky Mountain states (respectively), and the lowest diesel prices are typically found in the Gulf Coast states.

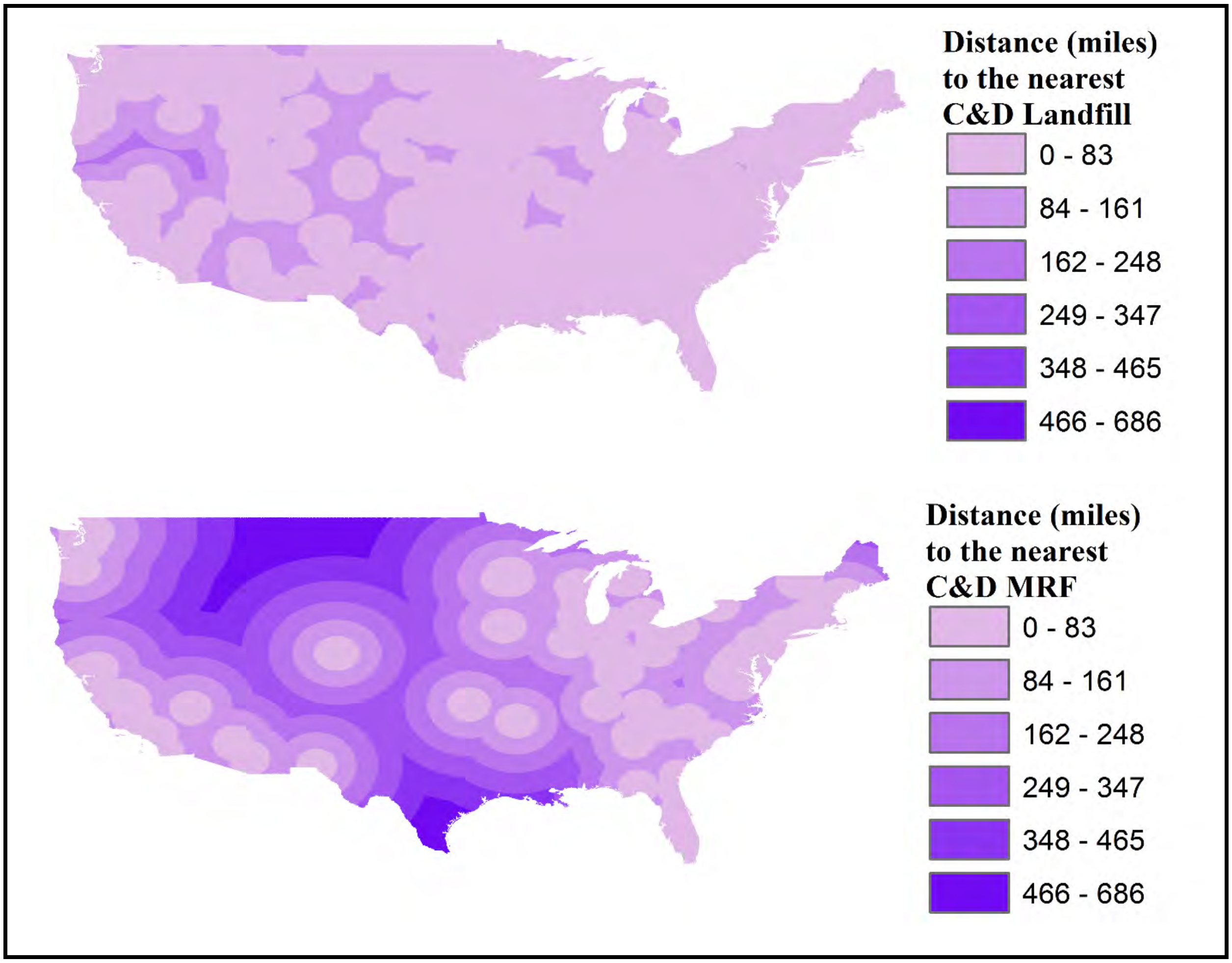


Figure 3-1. Distance in Miles to the Nearest C&D Landfill (Top) and Mixed C&D MRF (Bottom) (USEPA, 2014a [C&D Landfill Locations] and WBJ, 2012 [Mixed C&D MRF Locations])

Contractors can self-haul materials to a disposal or recovery facility, hire a hauling contractor, or use C&D recovery/disposal facility hauling services to transport materials. Commonly, roll-off containers are used at construction and demolition worksites to collect C&D. The hauling contractor transports the empty roll-off to the construction site, and the container remains onsite until it is filled or a predetermined rental period is reached (e.g., 7 days). Once filled, the hauler picks up the container and delivers it to a disposal facility or MRF. This delivery can be done as a one-time service, or the container can be regularly emptied and returned for ongoing projects. Depending on the resources of a construction or demolition contractor, it may be more economical to use a hauling service rather than to provide their own equipment and employees to haul C&D.

Hauling Contractors may charge different fees based on the type of material, such as a reduced rate for segregated C&D loads (i.e., loads with only one type of C&D). Construction sites located far from an MRF may also be charged additional fees to account for extra transport costs.

3.1.4 Materials Storage

Traditional demolition practices face additional challenges in dense urban areas where staging space for demolition is limited (Dantata et al., 2005). This reduced staging space requirement is advantageous for deconstruction because the less mechanized strategies used in deconstruction require less staging space and may have less impact (e.g., noise, dust) on the surrounding community. However, multiple containers may be necessary to store the various materials removed through the deconstruction process. Restrictions in space for job site material separation can potentially be mitigated by selecting smaller containers with more frequent material collection, choosing containers with multiple compartments, carefully selecting the number and size of containers based on the current phase of the job and the expected quantity of materials to be generated, or a combination of these strategies (CSB, 2008; TIRN, 2005).

Whether the C&D contractor elects to manage materials through recovery or disposal, the cost of renting a roll-off will generally include the drop-off and pick-up transportation costs, the tipping fee, and other environmental fees. Roll-off hauling services may be owned by or may be a subsidiary of the recovery or disposal facility company. The rates of these services are based on the distance to and from the delivery endpoint, the size of the container, and the type and weight of materials being hauled. Haulers provide differently sized roll-offs, which commonly range from 10 to 40 cubic yards. Some companies charge a flat, all-inclusive fee, but the bins typically have weight limits—loads exceeding those limits are charged additional fees. Some facilities charge a flat fee for delivery and pick up (a container charge) with a separate per-ton fee. C&D projects with considerably heavier C&D materials (e.g., PCC) will likely have greater hauling charges than projects that generate lighter C&D.

3.1.5 Tipping Fees

The tipping fee for C&D disposal versus recovery is one of the primary economic factors that influence C&D EOL management. This section discusses regional variations in tipping fees associated with offsite recovery and disposal and reviews economic considerations with onsite material use. While tipping fees are presented and reviewed according to the region, it should be noted that these regional variations are the result of several factors. Some factors that may be contributing to this regional variation include market demand for the recovered materials, regulations on the disposal of C&D, policies encouraging reuse of C&D,

operational costs of disposal and reuse facilities, characteristics of the local C&D material stream, and local land value.

Figure 3-2 shows the average U.S. recovery facility tipping fee for various materials, summarizing the results of publicly available tipping fee data from 123 C&D landfills (in 41 states) and 85 C&D MRFs (in 25 states) including recyclers that accept only one type of material (IWCS, 2016). It is important to note that Figure 3-2 and Figure 3-3 are not intended to accurately portray average tipping fees for different C&D materials, regions, and management practices, but to roughly illustrate nationwide, material-specific and region-specific tipping fee variability. Of the landfills reviewed, only 9 offered prices for uniform loads of materials other than mixed C&D loads—these prices are not included in the figure. The observation that mixed C&D tipping fees are higher at recovery facilities compared to landfills reflects that C&D recovery facilities are generally located only in areas with greater landfill tipping fees; to remain competitive, C&D recovery will charge tipping fees similar to those at local landfills. When a price for an out-of-county customer was available, it was used instead of the resident price. When a different residential and business rates were available, the average of the two was used. Metal, PCC, and wood were accepted with no tipping fee at some MRFs.

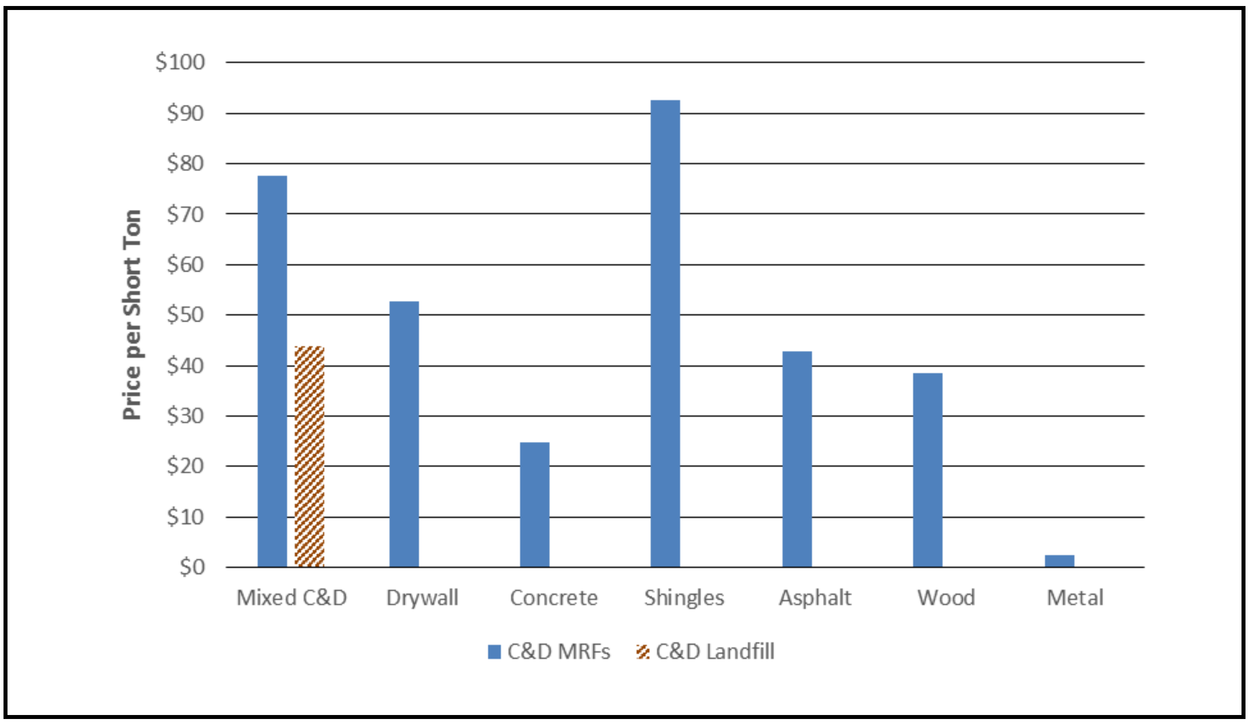


Figure 3-2. Tipping Fee Variability for C&D Materials in the United States (IWCS, 2016)

Figure 3-3 shows the regional variations in C&D MRF tipping fees, where the regions are organized per the U.S. Census Bureau's (n.d.) classifications. Mixed C&D tipping fees can vary widely with values ranging from $30 per ton to over $100 per ton. Tipping fees in the West and Northeast tend to be higher for mixed C&D than the U.S. average, and tipping fees in the Midwest and South tend to be lower. Variability in tipping fees may be driven by several factors, such as communities that have implemented mandatory recovery (which allows MRFs to charge higher fees without the need to be priced as competitively with landfills). MRFs, that have a tipping fee structure that varies by material, typically charge a higher fee for lower-value materials and materials that are harder to process/recycle (or dispose of) to cover the additional expenses necessary for managing the material. The tipping fee for non-asbestos asphalt shingles had the greatest range of values and the highest average tipping fee per short ton at C&D MRFs; the average tipping fee for this material exceeded the cost for mixed C&D. Metals, as previously described, have well-established recovery markets and most facilities charge no or minimal fees for them.

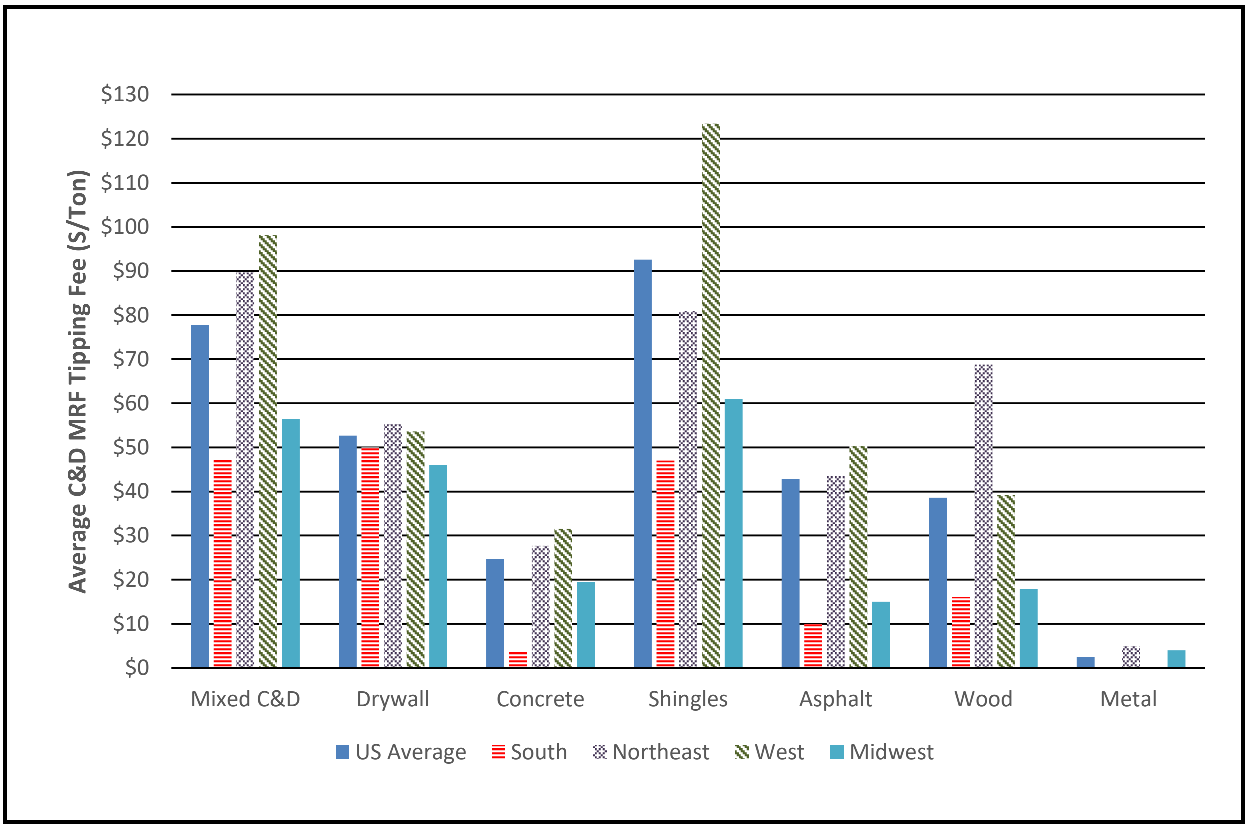


Figure 3-3. C&D MRF Tipping Fees by Region and Material for Several Facilities (IWCS 2016)

Additional fees or management costs may be incurred if harmful materials (e.g., lead-based paint, asbestos) are identified in discharged loads in the tipping area at C&D recovery or disposal facilities. Construction and demolition contractors are typically held responsible for properly disposing of any harmful or unacceptable materials discharged at recovery or disposal facilities.

The national average tipping fee at MSW landfills in 2013 was $49.78 per ton (USEPA, 2015b). In 2011, the weighted average tipping fee charged for C&D landfills was $31 per ton (WBJ, 2012).

3.1.6 Material Markets

> The local market and opportunity for recovery and reuse of C&D vary based on the material, the way the material is recovered, and the presence of contaminants.

The value of recyclable materials is often dictated by the current regional market forces. The demand for construction materials and supply of recoverable C&D materials varies over geography as well as time. Some materials, such as metal, have a relatively established market because their value is worth the cost of transporting the material long distances. Other materials, such as non-asbestos asphalt shingles, have strongly variable, region-specific demand.

The value of recovered materials compared to the value of the same materials manufactured from virgin resources also has a significant impact on material recovery. For example, asphalt pavement is one of the more commonly recycled C&D materials because it reduces the need for relatively expensive virgin asphalt. However, the cost of recovering dimensional lumber (e.g., through deconstruction) may be greater than the price of new lumber, which may discourage the recovery of this material.

3.2 Public Policy

3.2.1 Public Policy Options

Solid waste management public policy options may also influence C&D management decisions. State environmental and/or health departments have jurisdiction over solid waste management policy; this has created differences in how each state classifies and manages C&D (USEPA, 2015a). In some states, specific C&D materials may be exempt from solid waste public policy directives, which can allow more flexible EOL management options. In other states, depending on how C&D is defined, these materials may be banned from landfilling. C&D banned from landfills will require the availability of alternative management practices and communities that implement this policy would be expected to have an increased C&D recovery rate. Additionally, some state recycling goals prioritize recovery over landfilling C&D, as do local initiatives and incentives to encourage recovery. Table 3-2 summarizes public policy options that different state and local governments have used to help increase recovery.

Table 3-2. Policy Options for Promoting Solid Waste Recovery (Cochran et al., 2007)

Name	Description
Disposal Ban	A law or ordinance that specifically bans the disposal of certain waste materials from being disposed of in a landfill or restricted to certain landfills that have increased protection of the environment, such as Resource Conservation and Recovery Act (RCRA) Subtitle D or C landfills.
Disposal Tax	Artificially inflating the cost of disposal to make recycling or reuse a more economical option to the public.
Subsidized Recycling	Artificially decreasing the cost of recycling to make recycling or reuse a more economical option to the public.
Percentage Recycling Requirement	A law or ordinance that requires that a percentage of the waste stream be recycled.
Material Recycling Requirement	A law or ordinance that requires certain waste materials to be recycled.
Deposit/Advanced Disposal Fee/Rebate	A law or ordinance that requires the public to pay for disposal before waste generation (generally at the time that the building permit is applied for). This fee is returned if proof is provided that the material is recycled.
Government Waste Recycling Requirement	A law or ordinance that says that all government agency construction activity that produces waste (including C&D debris) must recycle or divert from the landfill some portion of that waste.
Government Recycling Purchasing Requirement	A law or ordinance that requires government agencies to purchase materials that have recycled content.
Business Development	Finances that are provided by the government to businesses to help develop recycling.
Education	Educational efforts performed by the government to increase recycling awareness specifically for C&D debris.
Recycling Goal	Legislation that provides a recycling percentage goal
Green Building	A regulation or legislation that encourages green building certification in the region.
Salvage Requirement	Demolition contractors are required to post notice of an impending demolition to allow parties to salvage materials from the building.

In addition, as demonstrated in Portland (OR), cities can adopt ordinances or building codes requiring deconstruction for particular types of buildings or historic buildings (City of Portland, 2017b).

Public policy impacts on C&D recycling are also seen in road construction. Many C&D materials have established uses in transportation applications, and guidelines and specifications established by federal and state departments of transportation (DOTs) affect the rate of C&D recycling for use as road base, in paving applications, and for other construction applications. As an example of the established support for the use of recovered materials in highway construction, over a decade ago, the FHWA (2002) published its policy on using recovered materials in highway applications, which included statements encouraging use and reducing barriers: "Recycled materials should get first consideration in materials selections…" and "Restrictions that prohibit the use of recycled materials without technical basis should be removed from specifications." This is an important aspect for the utilization of any reclaimed material since it must perform with known engineering properties that could differ from virgin materials.

3.2.2 Material Definitions and Exclusions

As previously mentioned, each state establishes its own set of solid waste public policy directives. These directives provide definitions of the materials the state considers to be C&D (and solid waste) and direction for how to manage C&D. These definitions often encourage recovery and reuse by exempting certain materials from solid waste public policy directives.

Because each state has adopted its own unique public policies, definitions of C&D vary throughout the country. C&D may be defined broadly as materials resulting from C&D activities. For example, one state lists that "[construction debris is the] solid waste derived from the construction, repair, or remodeling of buildings or other structures." Another state definition includes a specific list of materials that meet the definition of C&D, "…including but not limited to steel, glass, brick, concrete, asphalt material, pipe, gypsum wallboard, and lumber, from the construction or destruction of a structure as part of a construction or demolition project or from the renovation of a structure." A few states do not define C&D at all, but rather classify C&D as a different waste type; one state lists C&D under the definition of inert waste, while another includes C&D under the definition of rubbish. As a result of these different definitions, certain materials, or even classes of materials, may be considered C&D in some states but not in others.

There are also differences in the types of C&D materials that states exempt from public policy directives (examples presented in Table 3-3). Exempt materials have fewer management constraints and may be entirely excluded from solid waste public policy or may only be excluded in cases where they are beneficially reused, thereby reducing hurdles related to solid waste management such as permitting, material reporting, and documentation (USEPA, 2015a). Due to the less stringent directives for the management of materials no longer considered to be part of a waste stream, C&D recovery may be more economically competitive in states with C&D exemptions from solid waste management public policy. Exempt materials are typically deemed as inert or clean fill (e.g., bricks, blocks, rocks, soil), and to maintain exempt status, these materials cannot be commingled with other mixed C&D.

Table 3-3. Examples of C&D Exempt from Solid Waste Disposal Public Policy Directives in Five States (USEPA, 2015a)

State	Examples of Exempt C&D Materials
California	▪ Fully cured asphalt, uncontaminated concrete (including steel reinforcing rods embedded in the concrete), crushed glass, brick, ceramics, clay, and clay products for road work.
Delaware	▪ Asphalt shingles specifically used for recycling.
Iowa	▪ Asphalt shingles, glass, gypsum wallboard, rubble, or wood pre-approved for specific beneficial use applications.
Maine	▪ Chipped wood from LCD and timber-harvesting debris used at generation site (provided affected area is less than 1 acre in size). ▪ Inert material for fill, drainage material (for construction projects), or raw material for cement, concrete or asphalt production. ▪ Oil-contaminated soil stabilized with emulsified asphalt as aggregate for asphalt pavement production. ▪ Wood waste and land clearing debris (LCD) generated and combusted at the same facility in a specific set of combustion unit types.
Ohio	▪ Tree stumps in a C&D landfill. ▪ LCD used as fill at the site of generation/removal. ▪ Nonhazardous C&D including concrete, asphalt concrete, brick, block, tile, and stone, used as fill.

Note: These examples are only provided to illustrate the variety of C&D materials that may be exempt from solid waste public policy directives. These materials are typically only exempt from the solid waste public policy if used in specific applications. This table should not be used for C&D management purposes. State solid waste public policies should be reviewed for additional details.

Another example of how state C&D public policy variability can affect C&D recovery is the classification of land-clearing debris (LCD). Some states include LCD in the definition of C&D, others exempt it from solid waste public policy directives, and others evaluate the exemption of LCD used as a clean fill on a case-by-case basis. Since there is often no requirement to track the quantity of construction and demolition materials that are exempt from the state's definition of C&D (or solid waste), and due to the differences in the types of materials that fall within or outside states' C&D definitions, some states may be accounting for recovered C&D materials that others are not.

State public policy directives commonly list the types of facilities that may receive and manage C&D, such as MSW landfills, different classes of landfills specific to the state, inert waste landfills, and various types of recovery facilities (USEPA, 2015a). All else being equal, the cost of C&D disposal/recovery may be lower in states that have provisions for C&D management at a wider variety of disposal/recovery facility types. State public policy may also impact the cost of different C&D management options by having different material tracking directives for C&D disposal facilities compared to C&D recovery facilities. At least one state has provisions that do not require smaller C&D processing facilities (i.e., less than 50 tons per day) to obtain a solid waste management facility license—only facility registration is necessary.

Some states and local jurisdictions have banned C&D from landfills. For example, Massachusetts has banned certain C&D management methods; it first implemented disposal, combustion, and transfer bans for major C&D materials in 2006. The materials banned from these management practices included asphalt pavement, brick and concrete, metal, and wood (though wood could still be sent to an incineration facility). Clean gypsum wallboard was added to the list of banned materials in 2011 (MassDEP, 2014). A study conducted after the implementation of the wood disposal ban concluded that while the ban increased the amount of C&D waste being processed, it also may have increased C&D management costs for C&D generators (DSM Environmental Services, Inc., 2008).

In January 2015, Vermont implemented a ban on the landfilling of architectural waste (including drywall, scrap metal, asphalt shingles, clean wood, plywood, or oriented strand board) from projects that produce 40 or more cubic yards of architectural waste at a commercial project located within 20 miles of a solid waste facility that recycles architectural waste. Clean wood waste was proposed to be banned starting in July 2016 (VT DEC, 2014).

Other states have banned landfilling of materials that may be a component of C&D, such as cardboard or white goods (e.g., appliances); however, in general, major components of the C&D stream (e.g., PCC, asphalt pavement, drywall, and asphalt shingles) are not being banned at the state level. In Washington, demolition and inert waste can be accepted at limited purpose landfills and inert waste landfills. However, although a statewide ban on landfilling drywall does not exist, the definition of demolition waste excludes "plaster (i.e., sheetrock or plasterboard) or any other material, other than wood, that is likely to produce gases or a leachate during the decomposition process" (Washington Administrative Code, Title 173 Chapter 304 Section 100). This exclusion of drywall/sheetrock from the definition of demolition material may deter its disposal in limited use landfills.

In California, jurisdictions are encouraged to report C&D landfill bans as part of their annual diversion reports. Some counties have incorporated landfill bans with their recovery ordinances, although C&D has not been banned from landfills at the state level (CalRecycle, 2009).

The banning of certain C&D materials from landfilling is a method that states and municipalities have used to increase C&D recovery. Successfully implementing such a public policy directive necessitates careful planning. Developing C&D recovery infrastructure, researching whether adequate recovery markets exist or how to develop them, providing comprehensive guidance to communities, and developing a method to encourage adherence to public policy directives are all important aspects of that planning process.

Although some states are banning certain C&D materials from landfilling, smaller fragments of those materials may still end up in landfills when the use of C&D fines as landfill alternative daily cover (ADC) is allowed. State public policy directives which discuss whether C&D fines (i.e., RSM) can be used as ADC and whether this use counts towards state or local waste recovery goals vary from state to state. However, it appears that states commonly include a provision that allows alternative cover materials (such as C&D fines) to be used provided the alternate material performs to the same standards as cover soil. Please see Section 3.4.7 for more details on considerations related to the use of C&D fines as ADC.

3.2.3 Federal and State Recovery Goals

The Federal government is the largest real property owner in the United States with a domestic building inventory of approximately 300,000 owned and leased buildings requiring approximately $21 billion of annual operation and maintenance expenditures (Executive Office of the President of the United States, 2015). The federal government’s goal of diverting at least 50 percent of non-hazardous construction and demolition materials and debris (Executive Order 13423, 2007 & Executive Order 13693, 2015) has incentivized and promoted C&D recovery in federal building projects.

Many states have set recycling rate goals for solid waste to promote material recycling. Increasing C&D recycling has been perceived as a key to achieving these aims because C&D typically comprises a large proportion of the total quantity of discarded materials. Examples of some state recovery goals that include a C&D recycling component are presented in Table 3-4.

Some states (e.g., Delaware, New Jersey) have separate recovery goals for different types of material streams, or have different recovery goals for different areas (e.g., metropolitan/populous counties versus rural counties); and some have different recovery goals for various material generation sectors (e.g., residential, commercial, industrial). Also, while state diversion goals can increase material reuse rates and reduce the overall C&D generation and virgin material consumption, these benefits are not easily measured and counted toward meeting diversion goals that produced them.

Table 3-4. Examples of U.S. State Recovery Goals that Include C&D with Current Recycling Rates

State	Recycling Goal	Goal Target Year	Current Recycling Rate	Source
California	75% solid waste	2020	50% (2014)	CalRecycle (2014a, 2015)
Delaware	50% for MSW; 72% for all solid waste (including MSW, C&D, and other solid waste materials)	2015	41.9% (2013) MSW	DNREC (2015)
Florida	75% solid waste	2020	49% (2013)	FDEP (2013a, 2013b)
Massachusetts	None; proposed goal of 58% diversion rate by 2020 based on goal to reduce solid waste disposal by 30; 90% diversion rate by 2050 (zero waste goal)	None	42% (2009)	EEA (2013)
New Jersey	50% MSW; 60% Total	1995	54% (2012) Total	NJ DEP (2006a), DSHW (2014)
Oregon	50% MSW (includes some C&D materials)	2010	53.9% (2013)	DEQ (2011, 2014)
Texas	40% MSW (includes C&D)	—	18.9% (2013)	TNRCC (2002), TRDI (2015)

3.2.4 Local Policies and Initiatives

Although a state material management public policy might not include state-wide bans of C&D from landfills, some municipalities and counties within the state may choose to incorporate their own bans. Examples include Seattle and King County, Washington; Orange County, North Carolina; and many jurisdictions in California.

In 2012, Seattle Municipal Code 21.36.089 established a prohibition schedule for banning recyclable C&D materials from landfills. As of July 2014, asphalt paving, brick, concrete, metal, cardboard, and new gypsum scrap were prohibited from being sent to a landfill for disposal within Seattle. Unpainted and untreated wood was scheduled to be banned by

January 2015, and carpet, plastic film wrap, and tear-off asphalt shingles were scheduled for banning in 2017 (Department of Planning and Development, 2014; SPU, 2015). However, there are certain exceptions to this landfill ban including materials that are painted, have hazardous constituents, are difficult to separate from others, and are present in minimal quantities (SPU, 2015).

As of January 1, 2016, King County banned the following C&D materials from landfill disposal: clean wood (clean, untreated, unpainted); cardboard; metal; gypsum scrap (new); and asphalt paving, bricks, and concrete. Also, the county required that mixed and non-recyclable C&D must be sent to county-designated material recovery facilities or transfer stations (King County, 2017).

Orange County, North Carolina has a Regulated Recyclable Material Ordinance that includes bans on clean wood waste (excludes treated, painted, or stained wood), scrap metal, and corrugated cardboard (Orange County North Carolina, 2004, 2015).

C&D diversion initiatives and incentives at local levels, such as ordinances and deposit systems, also can impact C&D recovery. Table 3-5 summarizes several local diversion initiatives. The essential elements include incentives to increase diversion or penalties if projects fail to achieve certain recovery goals.

Lee County, Florida, is one example of a community with an established C&D diversion initiative (Lee County, 2007). This initiative, which was implemented in 2008, requires that recyclable materials generated and accumulated by multi-family properties, commercial establishments, and construction and demolition activities are source separated at the site of generation. The initiative has had a positive impact on the diversion of C&D from landfills; over 75% of applicable building project permit holders have opted to comply with the C&D diversion initiative (SWANA, 2011).

Portland, Oregon's C&D diversion initiative directs construction and demolition contractors to recycle at least 50% of wood, cardboard, metal, rubble, and LCD (City of Portland, 2005). During the project approval process, developers are given C&D recycling information that includes a one-page form on which they must explain how they plan to recycle the materials listed in the initiative. In 2008, the City of Portland (n.d.) established a 75% C&D material recycling initiative. In 2009, the city updated its Green Building Policy for city-owned facilities that directed recycling of at least 85% of all C&D from new construction and major renovations. Additionally, Metro (2010) implemented the Enhanced Dry Waste Recovery Program in 2009, which required Multnomah, Clackamas, and Washington counties in Oregon to deliver dry waste that is primarily composed of C&D to a Metroauthorized MRF. In 2016, Portland became the first city in the country to ensure C&D materials from older homes and duplexes are salvaged for reuse instead of crushed and landfilled.

Table 3-5. Examples of County- and Municipality-Implemented C&D Diversion Initiatives

Lee County, Florida	
Effective Date	January 1, 2008
Policy Diversion Rate	50%
Details	Not applicable to: ▪ Projects limited to plumbing work, electrical work, or mechanical work ▪ Construction projects less than $90,000 and alterations less than $20,000 ▪ Roofing projects that do not include removal of the existing roof In the event of deviation from the recycling initiative, and if a waiver reducing the diversion percentage was not granted, a diversion fee would be assessed.
Portland, Oregon	
Effective Date	October 31, 2016
Policy Diversion Rate	N/A
Details	• A demolition permit for a house or duplex must deconstruct the structure if it was built in 1916 or earlier or is a designated historic resource. • Previously, less than 10 percent of houses were deconstructed; now approximately 33 percent of single-family demolitions are subject to the deconstruction requirement
Effective Date	October 10, 2008
Policy Diversion Rate	75%
Details	Not applicable to: ▪ Projects valued at less than $50,000 The first deviation from the recycling initiative may be subject to an assessment of up to $500. The second deviation may be subject to an assessment of up to $1,000. Third and subsequent deviations may be subject to an assessment of up to $1,500. Assessments may be imposed per month, per day, or per incident.
San Mateo, California	
Effective Date	2002
Policy Diversion Rate	100% of asphalt, concrete, rock, stone, brick, sand, soil and fines and 50% of remaining materials
Details	• Contractors encouraged to make every structure planned for demolition available for deconstruction, salvage, and recovery prior to demolition and maximize recovery of reusable and recyclable materials prior to demolition. • Materials recovered through deconstruction and salvage are counted toward diversion requirements • Diversion to facilities approved by the County.
San José, California	
Effective Date	2001

Lee County, Florida	
Policy Diversion Rate	50% for private projects; 75% for public projects
Details	In lieu of a deposit, the following projects are required to pay a nonrefundable flat fee: ▪ New construction, demolition, and nonresidential additions greater than 1,000 square feet in size ▪ Nonresidential alterations greater than $200,000 in value ▪ Residential alterations and/or additions that increase a building's area/volume Abandoned project deposits and those not eligible to be returned support a variety of city activities.
Lake County, Illinois	
Effective Date	January 1, 2014
Policy Diversion Rate	75%
Details	Not applicable to: ▪ Construction, renovation, demolition, entire re-roofing, or entire re-siding projects of less than 1,500 square feet In the event of deviation from the C&D Compliance Plan, the plan shall be returned to the applicant and be marked as "Failed," but the applicant may make necessary changes and resubmit the plan. In the event of failure, the Administrative Adjudication Hearing Officer may assess fines.
Madison, Wisconsin	
Effective Date	January 1, 2010
Policy Diversion Rate	70%
Details	Not applicable to: Remodeling projects with a value of less than $20,000
Township of Woolwich, New Jersey	
Effective Date	2007
Policy Diversion Rate	65%
Details	Not applicable to: ▪ Roofing projects that do not include the tear-off of the existing roof ▪ Installation, replacement, or repair of a retaining wall, carport, patio cover, balcony, trellis, fireplace, deck, fence, swimming pool or spa, prefabricated sign that does not require modification to the structure to which the sign is attached, and storage racks ▪ Projects requiring only an electrical permit, only a plumbing permit, or only a mechanical permit Depending on the number of deviations from the initiative, project owners may be fined from $50 up to $5,000.

Forty-seven percent of California counties representing 88% of the total state population have implemented C&D diversion initiatives based on suggested legislation drafted by the state (CalRecycle, 2014b). The wide adoption of these C&D diversion initiatives is due to the state's targeted goal of 75% solid waste recycling by 2020. Some California jurisdictions set different diversion requirements for various materials. In Alameda County, California, nine local governments have required the diversion of 100% of C&D concrete and asphalt and at least 50% of the remaining C&D (StopWaste, 2016).

The Solid Waste Agency of Lake County (SWALCO), Illinois, amended its Solid Waste Management Plan in 2013, directing diversion of 75% of all C&D generated by new construction, renovation, demolition, entire re-roofing, or entire re-siding projects of 1,500 square feet or greater gross floor area (SWALCO, 2013).

Starting in 2010, Madison, Wisconsin, established a directive that new construction projects that use concrete and steel support recycle 70% of their construction debris by weight (the City of Madison, WI, n.d.). New construction projects that use wood framing and remodeling projects with a value in excess of $20,000 must recycle clean wood, clean drywall, shingles, corrugated cardboard, and metal. The city diverted 66% of waste from landfills in 2011, due in part to the construction and demolition program (City of Madison, 2011).

In 2007, the Township of Woolwich (2007), New Jersey, adopted a C&D recycling initiative requiring that 65% of C&D be diverted from landfill disposal. The New Jersey Department of Environmental Protection (NJ DEP) observed that, due to the implementation of the initiative, recycling rates in Gloucester County increased from 49.7% in 2006 to 54.8% in 2007 and to 59.1% in 2008 (NJ DEP 2006b, 2007, 2008).

3.3 Corporate Policy

Like public policy, corporate policies may also have an impact on C&D management practices. For example, numerous corporations have made it a policy to use the U.S. Green Building Council's LEED certification for building projects. Johnson and Johnson (2012) instituted a policy that all new construction and major renovations (totaling $5 million and all standalone buildings of lesser value) must meet the requirements of "LEED Certified or Equivalent." Similarly, all new facilities and renovations at Avon must be designed and built in accordance with the LEED Green Building Rating System, and Avon (2016) highlights five facilities that have received various LEED certifications. Google (n.d.) sets goals and benchmarks for building performance based on LEED, the Living Building Challenge, or other green building standards and rating systems; the company claims over 4 million square feet of LEED-certified buildings.

Like public policy, corporate policies may also have an impact on C&D management practices.

The prevalence of corporate C&D management policies is also noticeable in the marketing that several large-scale, waste handling/management companies employ to capture waste management contracts. Progressive Waste Solutions, Waste Management, and Republic Services advertise that their C&D collection and recovery services meet LEED's waste management requirements and help businesses achieve LEED certification (Progressive Waste Solutions, Ltd., 2016; Republic Services, 2014; Waste Management, 2016).

No corporate deconstruction/demolition policies were identified outside of those that appeared to be a direct result of public policy directives.

3.4 Material Markets

3.4.1 Marketability

Physical and chemical characteristics of recovered C&D are important factors in determining their suitability for a specific recycling use/end market. For example, C&D materials are commonly recovered and used as secondary materials to replace virgin materials in construction applications (particularly in road projects). Because the utilization of these materials can impact the overall strength and durability of the final product (e.g., a road, bridge, or building), the suitability of recovered C&D materials must typically be demonstrated through rigorous testing prior to approval. In this case, the technical specifications in national and state-specific highway transportation guidelines and Federal Aviation Administration (FAA) guidelines for airport construction help C&D recyclers and construction contractors navigate appropriate uses for recovered C&D materials in construction applications. Table 3-6 presents a summary of material-specific considerations that influence the viability of a given end-use market for different C&D materials.

Table 3-6. Summary of Markets and Unique Recovery Considerations by Material

C&D Material	Major Material-Specific Markets and Considerations with Recovery
Portland Cement Concrete	Commonly recycled as aggregate in transportation applications; sometimes recycled in place (after processing) as a fill material; must meet specifications in construction applications; the presence of rebar and large oversize pieces are factors impacting market suitability.
Asphalt Pavement	Most commonly recycled into new asphalt pavement, sometimes recycled in place, recycling can help reduce the high cost of raw material (asphalt).
Gypsum Drywall	Quality; the amount of paper in processed gypsum drywall (in remanufacture); few U.S. recovery facilities; competes with FGD gypsum in the manufacture of new drywall; state and local restrictions may apply for land application, which is historically the major reuse application where approved.
Wood	Identification and removal of treated or painted wood; large trees and stumps cost more to process; wood processors typically charge less than for other C&D materials; meeting boiler fuel specifications (e.g., moisture content, size, the level of contaminants); leaching concerns with mulch and boiler fuel ash.
Asphalt Shingles	Used in paving applications but not universally; can offset some of the pavement virgin asphalt cost; must be non-asbestos; must meet specifications in construction applications.
Fines and Residuals	Fines typically used as alternative daily cover for landfills and residuals may be used as a refuse-derived fuel; the amount of drywall in fines a major consideration for use in landfill cover applications since drywall presence is directly related to the potential for hydrogen sulfide release; contaminant level and moisture content of residuals are major considerations for marketability as a fuel.

3.4.2 Portland Cement Concrete

PCC can be accepted at a mixed C&D MRF or a designated PCC (aggregate) processing facility (often referred to as a concrete crushing plant); large amounts of PCC are most often managed at dedicated concrete crushing operations. Two factors that may influence the acceptability of PCC at receiving facilities are the size of the PCC pieces and whether they contain rebar. Some facilities specify the acceptable size of PCC pieces that can be accepted (usually less than 2 feet) and may charge a higher fee for larger pieces. Most facilities accept PCC with rebar, but protruding rebar may be required to be cut to a specified length (e.g., less than 2 feet). Some facilities do not accept PCC with rebar or charge a higher fee, which may influence a contractor's decision to choose PCC disposal over recovery.

PCC processing facility tipping fees vary locally and depend on factors such a local landfill tipping fees and the availability and cost of comparable aggregate products from virgin sources. As with other C&D materials, facilities charge by the truckload, cubic yard, or ton. Example tipping fees identified as part of the IWCS (2016) study included PCC processors that may accept material free of charge, one that charged $16 per ton in one area of the country, and another that charged fees between $50 and $1,000 per truck load in a different location. Mixed C&D processors will typically not take PCC free of charge, and their fee will generally be higher than the fee charged by PCC processors.

PCC recycling operations, whether as part of a mixed C&D recovery facility or PCC crushing plant, produce various products. Some state DOTs have published specifications for specific recovered concrete products for applications such as road base. Through various crushing, screening, re-crushing, and re-screening steps, crushing facility operators produce DOT-specified products (as applicable) and create a wide variety of other products to meet local market demands. The prices charged to customers for their products depend on local market needs for the specific products and the market prices for comparable virgin products. Facilities may sell crushed concrete products on either a per-ton or a per-cubic-yard basis, and publicly available product prices ranged from $5 per ton to $22 per ton and $6 per cubic yard to $20 per cubic yard (IWCS, 2016).

In addition to being recovered at C&D MRFs and designated aggregate facilities, PCC has also been recycled at project sites. Many companies offer mobile crushing services that serve the locations where the crushed PCC will be used for construction. Crushing PCC onsite saves the cost of transporting PCC between a crushing plant and construction site, in addition to saving costs of purchasing new construction materials.

As shown in Figure 3-4, several states are using recycled concrete aggregate (RCA) as an ingredient in road bases.

The Construction & Demolition Recycling Association (CDRA) conducted a survey related to the use of RCA in all the states and discussed the cost savings of using recycled PCC aggregate with several state materials engineers (CDRA, 2012). Responses suggested that using RCA instead of virgin aggregates could provide cost savings ranging from $2 to $4 per ton (up to $6 per ton in areas lacking natural aggregate resources). The cost of recovered PCC has remained relatively constant over time, varying from about $5 per ton to $7 per ton between 2003 and 2014 (USGS, 2015). Figure 3-5 shows the 2013 price of recycled PCC based on data from the U.S. Geological Survey (USGS, 2015). It seems likely that a primary factor depressing the price of RCA for a given location is the availability of, or proximity to, virgin aggregate (e.g., limestone, granite) resources.

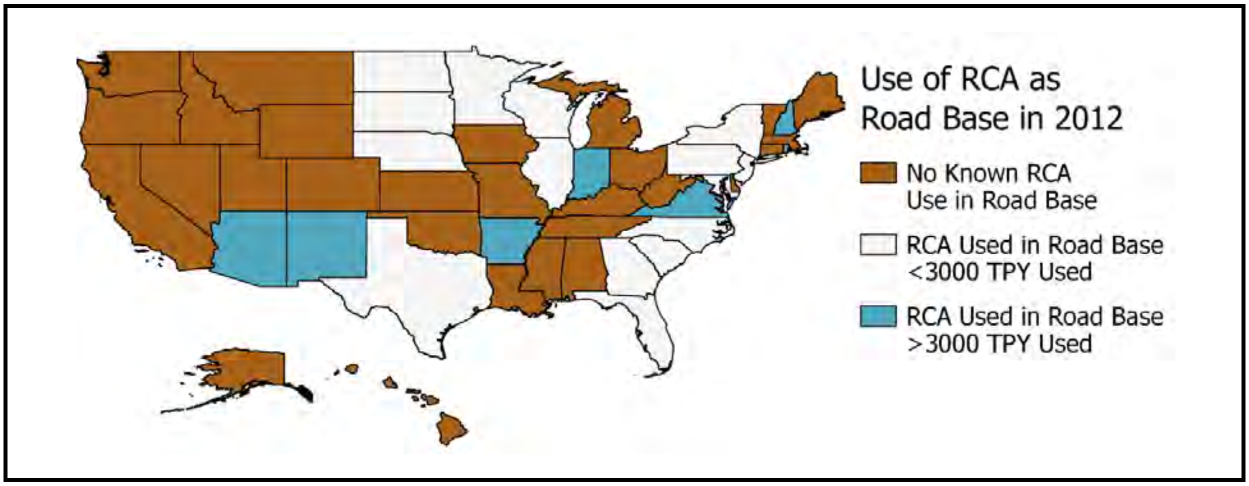


Figure 3-4. U.S. RCA Application in Road Base (CDRA, 2012)

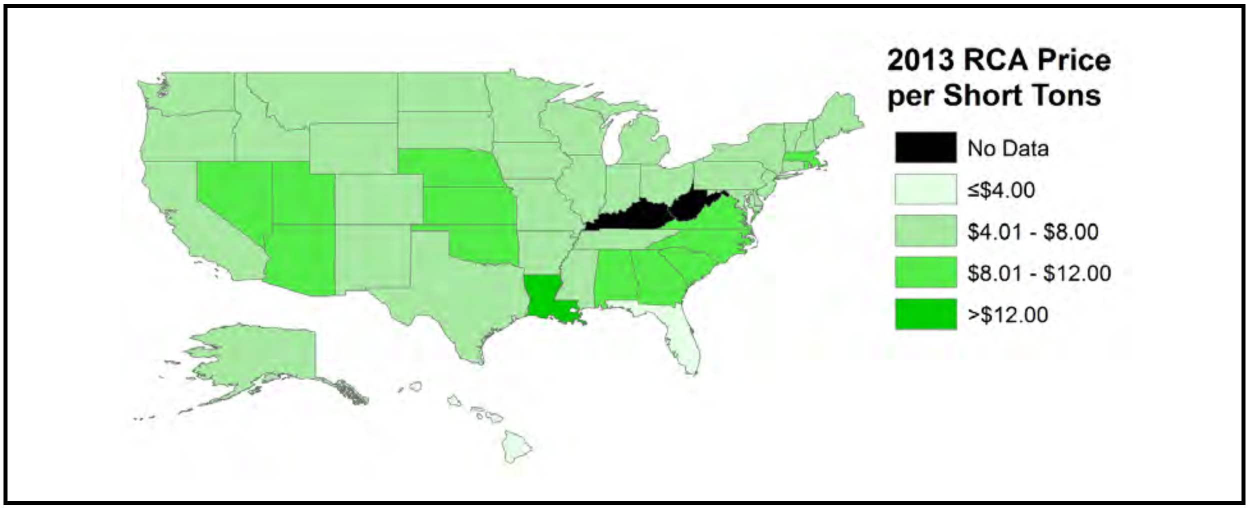


Figure 3-5. 2013 RCA Price by State (USGS, 2015)

While RCA is commonly recycled at the site of generation and used in transportation projects, the FHWA reviewed the five states consuming the most RCA—Minnesota, California, Virginia, Texas, and Michigan—and observed that although PCC is commonly recovered and primarily used as a road base material, the use of RCA as aggregate in HMA and PCC is not as widely accepted (FHWA, 2004). The use of RCA as a virgin aggregate substitute is limited in the production of new PCC because this use is typically not approved by state DOTs. It appears that the lower compressive strength of RCA also makes it less desirable for use as an aggregate substitute in HMA mixes.

RCA used in transportation applications must meet appropriate specifications (e.g., strength, gradation). Out of 40 respondents to CDRA's survey, 33 states allow the use of RCA as a base material (CDRA, 2012).

The FAA (2014) Airport Construction Standards (AC150/5370-10) provide specifications for the use of RCA as a base course under airport pavements. Comparing the requirements for RCA base course and virgin crushed aggregate base course, there are some differences and additional requirements and restrictions for the use of RCA base course. Table 3-10 provides examples of some of the provisions of these specifications. As described in FAA (2014), up to 10% (by weight) of the RCA base course can consist of foreign material; Table 3-7 provides the maximum amounts of particular foreign materials. Also, FAA (2014) waives the sodium sulfate soundness test that is required for the virgin aggregate materials. The waiving of this test and the allowance of some foreign material in RCA could make it easier for contractors to obtain material that meets construction standards; however, the other two listed specifications with respect to weight and soil type could limit the use of RCA in some airport construction projects.

Table 3-7. Example Specifications for RCA Use as Base Course at Airports (FAA, 2014)

Specifications	Recycled Concrete Aggregate Base Course
Allowed foreign material (by percent weight)	The total foreign material must be less than 10%, individual material limits: • Wood (0.1%) • Brick, mica, schist, or other friable materials (4%) • Asphalt concrete (10%)
Weight restrictions	Recommended restrictions to where RCA can be used in the pavement when loads are greater than 60,000 pounds.
Other restrictions	Not to be used in locations with high sulfate content soils (no more than 0.5%).

There are also examples of local governments that have established requirements for using recovered PCC (and often asphalt pavement) in road construction applications. In 1995, the City of Los Angeles began requiring city projects to use 100% recovered asphalt, PCC, and other inert materials (crushed miscellaneous base) in city projects that require road base (CalRecycle, 2014c). Requiring recovered materials in construction and transportation applications may assist in developing a local market for materials that local PCC processors produce and sell. CalRecycle (2014c) identifies several other local governments (e.g., cities of Modesto and Palo Alto, and Butte County) in California that have promoted the use of recovered aggregates in city and county projects. Specifications for the use of recovered aggregate in California can be found in Caltrans' specifications and the *Greenbook* (*Standard Specifications for Public Works Construction)*. The 2010 Caltrans specification allows up to 100% use of recovered aggregate (which can include reclaimed PCC and processed asphalt concrete) for both base and subbase aggregate applications (Caltrans, 2010).

3.4.3 Asphalt Pavement

Asphalt pavement is commonly recycled back into new asphalt pavement mixes. Asphalt pavement incorporated into new hot mix asphalt (HMA) provides a source of aggregate and binder. The fraction of newly placed asphalt consisting of RAP in 2013, by state, is shown in Figure 3-6. Most states used reclaimed asphalt pavement (RAP) in HMA generation in the range of 11% to 32% (NAPA, 2014). The regional variation in the price of RAP as obtained from USGS (2015) is shown in Figure 3-7. Based on these numbers, the price of RAP appears to have little correlation with the fraction of RAP used in new asphalt.

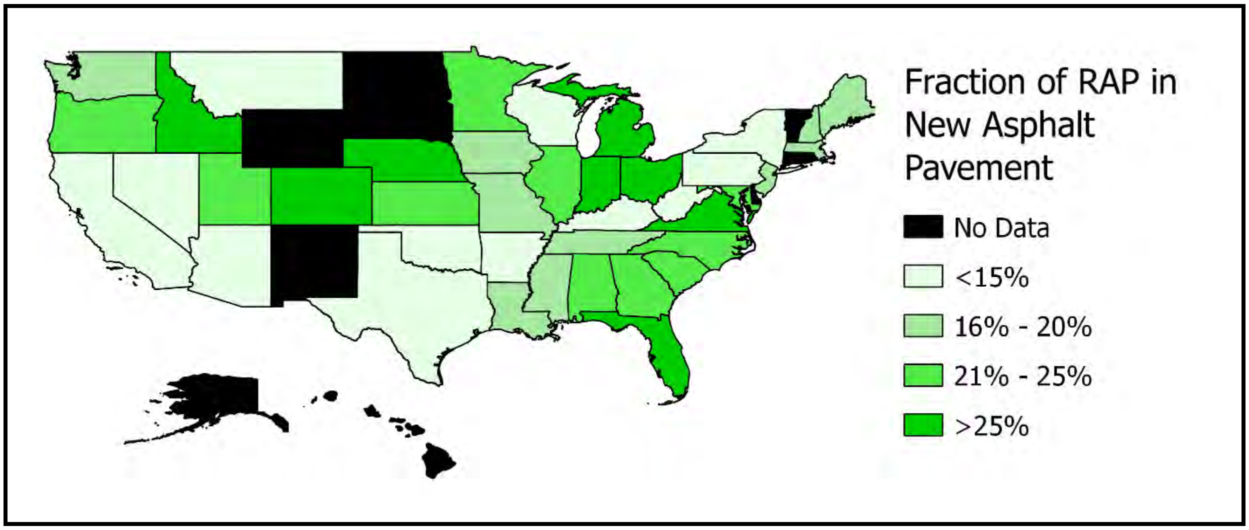


Figure 3-6. 2013 RAP Fraction in New Asphalt Pavement (NAPA, 2014)

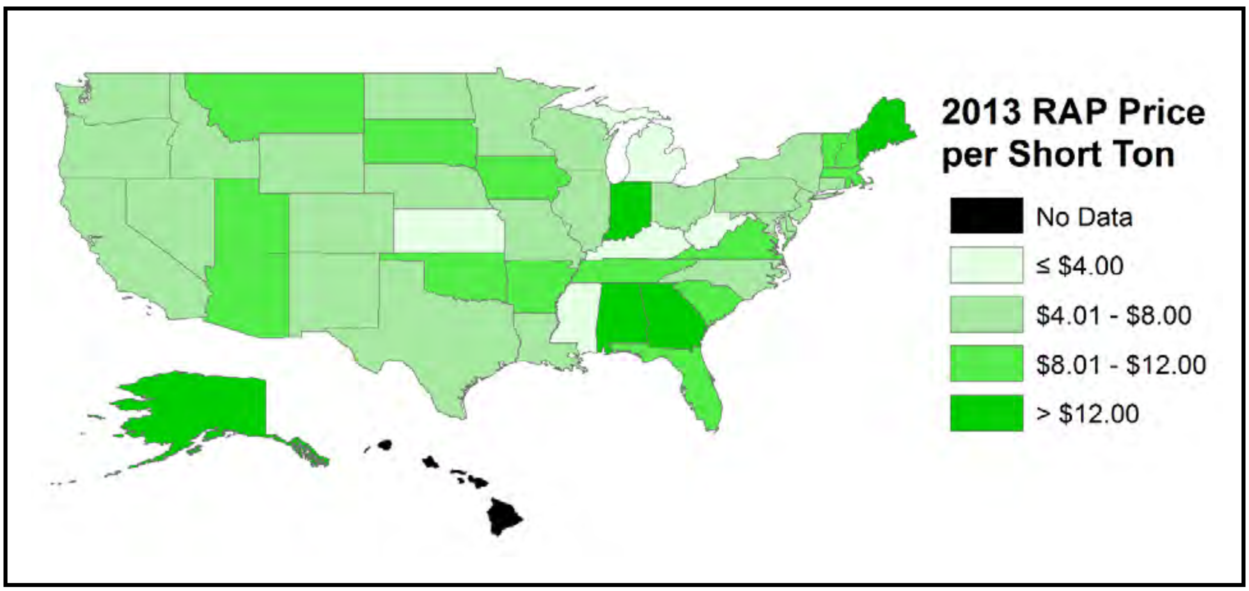


Figure 3-7. 2013 RAP Price by State (USGS, 2015)

While the price of RAP appears, on average, similar to that of RCA, it has fluctuated more over the same period from 2003 to 2014 and has varied from approximately $5.50 per ton to nearly $10 per ton (USGS, 2015). This fluctuation is likely impacted by the relationship in virgin asphalt and oil prices.

FHWA (2014) provides specifications for asphalt pavement construction (with HMA), which limits the use of RAP to no more than 20% by mass of a mix′s composition. For each different mixture of HMA, FHWA (2014) also requires details on RAP used in the mix to be submitted for verification and for pavement test strips to meet targeted criteria. Details on the RAP used in the mix that must be reported include the source and percentage of RAP in the mix, the specific quantities of the different aggregate sizes/aggregate gradation of the RAP, specific gravities of RAP stockpiles, percentage asphalt binder in RAP, and samples of RAP used from each stockpile to be used in construction projects.

However, the amount of RAP used in asphalt mixes appears to be increasing with the use of pavement mixes, with 30% to 50% RAP becoming more common (West and Willis, 2014). When higher percentages of RAP are employed in HMA, additional mix testing requirements may become necessary. For example, Washington State DOT (WSDOT, 2014) allows for HMA production with greater than 20% RAP by total weight. If greater than 20% is used, the RAP is to be processed such that 100% passes a sieve twice the size of the maximum aggregate size for the class of mix to be produced.

3.4.4 Drywall

The primary markets for recovered drywall are soil amendments and in the manufacture of new drywall. Recovered drywall has also been used as a gypsum substitute in the production of Portland cement. Few processing facilities focus exclusively on drywall, but several C&D MRFs accept drywall.

Two drywall recyclers (facilities accepting gypsum drywall as the only C&D material) were identified in the United States, one in the Northwest and one in the Northeast. The company that owns the Northwest site is in Washington State and accepts construction and demolition drywall (including drywall with paint and wallpaper) from public sources, and wet or dry gypsum drywall from manufacturers. As of the time of information gathering for this report, their tipping fee for waste drywall was $85 per metric ton. It is estimated that the plant can recycle and process 25 tons of drywall per hour (New West Gypsum, 2015).

The gypsum recycler in the Northwest United States was the only identified recycler/ processor producing gypsum from demolition drywall exclusively for use in the remanufacture of drywall. As discussed in Section 2.3.6, drywall manufacturers often recycle preconsumer drywall back into the production of new drywall, but recycling of postconsumer drywall into new drywall is not common. The material must meet specifications that allow only small amounts of paper in the gypsum mix, and it may be difficult for smaller recyclers to achieve these minimum standards.

The gypsum recycler in the Northeast (i.e., Pennsylvania) has two facilities and has recycled drywall for nine different states (USA Gypsum, n.d.). This recycler accepts mostly scrap drywall from other C&D recyclers, but scraps from construction contractors and off-specification drywall from manufacturers are also accepted. Demolition drywall cannot be recycled at these facilities. The recycler estimated in 2011 that over 30,000 tons of drywall were managed at their facility. The recovered drywall is processed and ground into mostly agricultural products (granular, pulverized, and ultrafine gypsum for amending soil). Various types of animal bedding and other products are advertised as well.

C&D drywall gypsum used in drywall manufacturing must compete with flue gas desulfurization (FGD) gypsum, the synthetic gypsum produced at coal plants as a byproduct from air pollution control "scrubbing" devices. One gypsum drywall manufacturer advertises drywall products consisting of 99% recycled materials, which uses FGD gypsum exclusively for the drywall gypsum core (Continental, 2015). Since FGD gypsum is a byproduct of the coal combustion process and coal plants would otherwise pay for the material to be managed, FGD gypsum generally is an inexpensive material that drywall manufacturers can access. Unlike postconsumer drywall, FGD gypsum is free of paper contamination.

States and local communities often provide standards for the application of gypsum produced from C&D drywall. These conditions broadly require that drywall cannot be contaminated with non-drywall materials (e.g., paint, glue), must be processed to a certain size, can only be applied to particular types of land that need fertilizer, and cannot exceed a location-specific application rate.

Some facilities accept drywall but do not actually recycle it due to inefficiencies in transportation and recoverable costs. The tipping fee structure for facilities throughout the United States for C&D MRFs that charge a different fee for drywall compared to mixed C&D material ranged widely, from $12 per ton to $93 per ton, with MRFs in the Northwest charging among the highest rates (IWCS, 2016). Most facilities were charging less for loads of drywall compared to mixed C&D; prices for drywall ranged from $10 more per ton to $85 less per ton (IWCS, 2016).

Cement kilns use gypsum in the production of cement to aid in the cement setting time. The gypsum is added post-kiln to the cement clinker as it is crushed in the ball mill. Although cement production is not an established market for recovered gypsum, some facilities have explored using drywall as a potential virgin gypsum substitute. However, this possible use requires special care to remove the paper and minimize the number of impurities from drywall.

3.4.5 Wood

Wood is the third-most used construction material in the United States after asphalt pavement and PCC. Approximately 60% of the total wood products consumed in the United States are used for residential and nonresidential building construction and renovation (Cochran and Townsend, 2010; Falk and McKeever, 2012). Wood is used in building structural frames, flooring, interior finishes, and outside structures such as fences. The wood waste generated by construction and demolition activities includes dimensional lumber (e.g., 2x4s, 2x6s), engineered wood (e.g., plywood, particle board, medium-density fiberboard, structural laminated veneer lumber, glue-laminated timber, wood I-joists), pallets, sawdust, tree stumps, branches, and twigs.

Estimates of wood waste vary. In 2013, approximately 40 million tons of wood waste was produced in the United States (USEPA, 2015b). Six C&D waste composition studies observed that wood waste ranges from 8% to 36% in C&D (CCG, 2006, 2008, 2009; CDM, 2009; R.W. Beck et al., 2010; USEPA, 2015b). Falk and McKeever (2012) estimated that approximately 52% of C&D wood waste generated across the United States is recovered.

There are limited options for reusing wood waste as building materials, and this practice is not common in the United States. Wood waste could be recovered and reused from building deconstruction projects, but this has been practiced only on a very small-scale (Denhart, 2010; NAHB, 1997). Furthermore, since not all cities have capabilities to grade structural wood for reuse, this need for grading can be a major challenge in its reuse.

The largest market for wood waste, since most wood is generated during demolition, is as a raw material for biomass fuel, and for mulch and compost production if the wood is clean. Wood waste in C&D may be mixed with other C&D materials that then need to be separated at C&D processing facilities. Once separated from other C&D, wood waste can be size reduced and processed to desired specifications depending on the intended use of the product.

Biomass-to-fuel facilities can potentially use C&D wood waste as a raw material. Eighty facilities in the country are listed by the Biomass Power Association (n.d.). Jambeck et al. (2007) observed that 280,000 tons of C&D wood waste release 1.2 million more BTU when combusted than the same amount of virgin wood and emits less particulate matter, nitrogen oxides, sulfur dioxide, and carbon monoxide. Air pollution emissions are an important regulatory consideration for biomass facilities. Biomass facilities burning fuel such as C&D wood previously had to comply with air pollution regulations promulgated under the Clean Air Act (CAA), Section 129. In December 2011, the USEPA amended the rule related to Non-Hazardous Secondary Materials, which allowed biomass facilities that burn C&D to instead meet the requirements of CAA Section 112 (Federal Register, 2011).

In 2016, USEPA classified additional C&D materials as non-waste fuels, including C&D wood processed from C&D according to best management practices, and creosote-treated railroad ties that are processed and combusted by certain types of combustion units (USEPA, 2016b).

In addition to regulatory concerns for using C&D wood waste as a fuel source at biomass facilities, moisture content and impurities in C&D wood waste (e.g., dirt) also need to be addressed by these facilities. Impurities and variable moisture content can impact the performance of the energy-generation operation, and thus for quality control purposes, facilities limit permissible levels of contaminants and the moisture content of the fuel.

Wood waste has historically been used for mulch production, which has the largest market share in terms of C&D wood waste recovery. The use of colored dye in mulch has also increased its popularity. Due to health concerns with treated wood and some types of painted wood, treated and painted C&D wood wastes are not suitable for use as mulch.

3.4.6 Asphalt Shingles

As previously discussed, postconsumer non-asbestos tear-off asphalt shingles are typically recycled in road paving applications. Between 2009 and 2013, the use of recovered asphalt shingles (RAS) in asphalt paving increased by approximately 135%, and by 2013, all but 12 states have used at least some RAS in paving applications (NAPA, 2014). Although RAS is widely used in pavement, each state sets its own limit on RAS use. For example, one state allows no more than 5% of RAS in its pavement while another has a 25% RAS mixture limit.

The tipping fee for asphalt shingles at MRFs throughout the country varies. Some MRFs charge the same rate as mixed C&D, some charge more for shingles-only loads, and some charge less for shingles-only loads. Compared to the tipping fee for mixed C&D material, mixed C&D processing facilities in the states examined charged from $40 less to $150 more per ton of asphalt shingles (IWCS, 2016).

RAS is used less commonly in pavement construction applications than RAP and RCA. RAS pavement mix specifications are continually changing and being updated. The American Association of State Highway and Transportation Officials (AASHTO) has provided guidelines for designing new HMA material using RAS. AASHTO recommends that the particle size and a binder content of the new HMA be determined, as the presence of RAS binder greater than 0.75% by weight can considerably change the performance grade of the HMA. AASHTO also provides estimation methodologies for determining the performance grade of new HMA, and the percentage contributions of RAS into new HMA (AASHTO, 2007).

3.4.7 Fines and Other Residuals

The two most common markets for C&D fines are landfill cover and soil fill/replacement. Landfills, whether for MSW, C&D, or other waste, rely on the application of soil cover to the surface of placed waste to help control windblown litter, odors, vectors, and fires. Soil cover also plays a critical role in controlling stormwater run-on and runoff. The conditions that constitute a suitable alternative soil cover include its ability to suppress fire (e.g., it cannot have too high a content of combustible materials) and a makeup that will not contaminate stormwater runoff. The use of C&D fines as alternative daily cover (ADC) is practiced in many areas of the country, but the allowable use in an area will depend on applicable public policy limitations and permit conditions.

An issue that has surfaced in the past decade concerning C&D fines and their use as ADC is the potential for producing hydrogen sulfide (H_2S) and other sulfur gases. Gypsum is often present at elevated concentrations in C&D fines (Townsend et al., 1998) due to drywall and plaster pieces passing through the screening equipment. In a landfill, the sulfate that leaches from the gypsum can be biologically reduced to H_2S, which poses problems because of its odor and other deleterious properties (Anderson et al., 2010; Tolaymat et al., 2013). Elevated H_2S can impact landfill gas recovery and conversion equipment, and some landfills may thus have concerns with the acceptance or use of C&D fines.

The successful use of C&D processing residuals in the refuse-derived fuel (RDF) market depends on the quality of the material and the ability of the C&D processor to identify and secure local market demand/end users. Potential buyers of this material include cement kilns and industrial boilers, and their specifications for acceptable fuels depend on their particular air emission permit conditions. One issue encountered by some C&D processing facilities is the need to minimize the amount of PVC plastic in the fuel stream since the combustion of PVC can lead to the production of harmful air pollutants such as dioxins and hydrogen chloride gas (Zhang et al., 2015). Figure 3-8 shows a C&D processing facility using a grinder to further process a fraction of its processing residuals into a refuse-derived fuel product.

Figure 3-8. Mixed C&D Processing Facility Grinding Mixed C&D Processing Residuals into a Refuse-Derived Fuel Product

4. IMPACT OF GREEN BUILDING MATERIALS ON C&D RECYCLING

This section of the report introduces the concepts of green building and green building materials and examines how they have been changing the C&D recycling landscape by replacing conventional materials for which there are established markets. In addition, to better understand the potential impact of green building materials, various green building certification programs are described, emphasizing their role in the adoption of green building materials.

4.1 Overview of Green Building Materials

The construction and operation of buildings require a significant amount of water, energy, and materials. Consequently, a large amount of waste is also generated. According to the U.S. Green Building Council (USGBC), buildings account for approximately 40% of total energy use, 40% of raw materials use, 30% of waste output, 13.6% of total potable water consumption, 73% of total electricity consumption, and 38% of greenhouse gas emissions (USGBC, 2015). In addition, over 4 pounds of waste are generated per square foot of building space during construction (USEPA, 2009). The construction process can have significant impacts on the surrounding environment and present challenges for local ecosystems. As the effects of construction have become more apparent, the field of green building has become increasingly popular.

4.1.1 Green Building

The USEPA defines green building as "the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation, and deconstruction" (USEPA, 2014b). Green building is used synonymously with sustainable building, sustainable development/design, natural building, high-performance construction, eco-construction, green construction, and green architecture. This report uses the term "green building" as defined by USEPA.

Green building is a growing trend due in part to government incentives and tax breaks at local and national levels for builders, developers, and homeowners. Examples of financial incentives for the green building include tax credits, fee reductions, and expedited permitting. The State of New York was the first in the nation to sign a green building tax credit into law in 2000. Over a 9-year period, it provided $25 million in income tax credit for owners and tenants of buildings that met certain criteria related to building size, construction materials, energy and water use, and select other issues (Kneeland, 2006). Houston offered property tax credits for commercial buildings that are certified through the LEED program (USDOE, n.d.). Maryland gave $25 million in tax credits to businesses between 2001 and 2005 for constructing and operating energy-efficient buildings under the state's green building tax credit program (MEA, 2015).

There are multiple environmental, economic, and social benefits to green buildings when compared with conventional buildings. They are described in the following sections.

Example Environmental Features

The environmental advantages associated with green buildings include:

- Air pollution reduction. Using local materials reduces transportation distances and the associated air emissions and petroleum consumption. Transportation costs for locally sourced materials are also lower, yielding cost efficiencies. Energy-efficient buildings require less electricity and reduce air emissions from power generation. Green buildings require the use of materials that generate fewer emissions, improving indoor air quality.
- Water pollution reduction. Green buildings employ high-efficiency water fixtures, which reduces water consumption, as well as the use of gray water recycling systems that filter and reuse water. If buildings include limited areas of impervious surfaces, stormwater pollution is also reduced.
- Waste minimization. The construction of green buildings aims to minimize site disturbance and involves the diversion of materials from landfills and incinerators, increasing C&D reuse and recycling. Retaining existing structures lowers material costs and generates less waste.
- Efficient energy use. When buildings are designed to use passive heating and cooling, the use of and wear on heating, ventilation, and air conditioning (HVAC) systems is minimized, as is energy consumption.
- Reduced impact on ecosystems, biodiversity, and natural resources. Choosing green building materials generally, reduces the environmental footprint and burdens on natural resources. Green buildings often incorporate renewable wood or products with recycled content. Using these products can reduce habitat destruction and deforestation.

Example Economic Features

Economic advantages associated with green buildings include:

- Operating costs reduction. Many green buildings incorporate long-lasting, durable equipment and materials, which require less maintenance and lower maintenance costs.

A decrease in energy consumption associated with energy-efficient equipment, such as energy-efficient lighting and heating, cooling, and water systems equates to a reduction in operating costs. Light-colored and vegetated roofs reduce cooling needs, further lowering energy costs.

- New markets developed for green products. Used building products that enter the C&D recycling market generate additional revenue.
- Green jobs creation. Consistent with the development of new markets for recovered C&D is the demand for a workforce that understands the industry from product development to product certification, distribution, and use. This may result in the creation of new jobs or may require retraining of the existing workforce.

Example Social Features

Social advantages associated with green buildings include:

- Healthier buildings that support improved occupant productivity, aesthetics, and quality of life. The use of natural lighting can enhance employee well-being and productivity at the workplace. Redevelopment of abandoned buildings helps surrounding businesses and the local economy, revitalizes neighborhoods, and prevents resources from leaving communities (USEPA, 2014b).
- Increased environmental awareness. Learning about the principles of green building may lead to changes in personal behavior and benefit the overall society. Lessons learned from obtaining green building certification can be applied to other work and future projects.

4.1.2 Green Building Materials

Standards-setting bodies and industry organizations are collaborating to examine the multi-attribute further, life cycle performance of building material types, potentially including and validating select examples in Table 4-1.

The use and recycling of green materials are integral to the green building process. Green building products use natural resources in an environmentally responsible way and are resource, energy, and water efficient (Spiegel & Meadows, 2010). They also improve indoor environmental quality. These additional benefits may result in a greater up-front cost compared to conventional building materials. Figure 4-1 illustrates the criteria often used to classify green building materials.

The green building materials characteristics can generally be grouped into four categories: 1) resource efficiency, 2) indoor environmental quality, 3) energy efficiency, and 4) water efficiency. Table 4-1 provides examples of materials with various characteristics commonly considered to offer benefits within these four categories.

Figure 4-1. Characteristics of Green Building Materials

Table 4-1. Examples of Building Materials with Potential Green Features (Spiegel & Meadows, 2010)

Use	Examples of Materials with Potential Green Features
	Resource Efficiency
Base, foundation	Autoclaved aerated, insulated concrete
Flooring	Bamboo, cork, linoleum
Insulation	Contains cellulose; cotton, fiberglass, mineral wool
Masonry	Adobe unit; rammed earth, stone assemblies, manufactured masonry
Roofs	Designed to incorporate live vegetation
Structural support	Recycled steel
Various (e.g., structure and siding)	Reclaimed lumber, Forest Stewardship Council (FSC)-certified wood
	Indoor Environmental Quality
Flooring	Carpet made of wool, cotton, jute, hemp, seagrass, sisal
Paint and glue	Volatile organic compound (VOC)-free/low-VOC, water-based, nontoxic
Lighting	Natural light

(continued)

Table 4-2. Examples of Building Materials with Potential Green Features (Spiegel & Meadows, 2010) (continued)

Use	Examples of Materials with Potential Green Features
	Energy Efficiency
Doors and windows	FSC-certified wood windows, low-energy glass, multipane designs
HVAC	Properly sized equipment
Lighting	Light-emitting diode (LED)
	Water Efficiency
Heating and cooling	Solar water heater or heat pump
Plumbing	Low-flow fixtures, automated controls, dual-flush option toilets

4.1.3 Prefabricated Components

Prefabricated components are frequently used in many types of building projects. In 2011, prefabricated components were used on more than half of the construction projects but on less than 25% of the individual project components. Continued market growth is expected (McGraw-Hill Construction, 2012). While the primary driver for their use is improved productivity, prefabrication and modularization have been reported to reduce onsite waste and decrease project materials use by at least 5% (McGraw-Hill Construction, n.d.).

4.2 Green Building Material Requirements in Various Certification Programs

The global market value of green construction materials was $116 billion in 2013, and that number is projected to grow to more than $254 billion in 2020 (Navigant Consulting, 2016). This growth in the availability of green building materials can be credited to an increase in the number and awareness of green building certification programs. These voluntary certification programs are intended to provide construction companies with the criteria for determining the performance of their buildings, and their adoption continues to increase. Green building rating and certification systems can be local, state, regional, national, or international programs. Some are broad in the environmental areas they address, while others address a specific issue, product, or sector. The types and quantities of new materials that have resulted from the increase in green buildings will change the character and composition of the C&D recycling stream in the future.

4.2.1 Green Building Certification Programs

Green building programs generally have similar goals regarding sustainable use of water, energy, and materials. LEED is the most common green building certification program in the United States. Its certification can be awarded to new or existing commercial, industrial, or residential buildings, as well as neighborhood developments or homes. Green Globes is primarily granted to commercial buildings, but is also available for institutional and multifamily residential buildings. The Living Building Challenge is an international certification that has been granted to both residential homes and commercial buildings. The National Green Building Standard (NGBS) applies to the residential sector, as well as to hotels and motels. It can be used for new homes and the sites on which they are built, home remodeling, and high-rise multifamily buildings.

LEED

Since its inception, LEED has transformed the high-performance green building industry and subsequently helped grow the green building materials market. Today, it is the most well-known and widely used certification program with standards that rate the environmental merits of new and existing buildings and entire neighborhoods.

LEED version 1.0, launched in 1998, focused primarily on the owner-occupied new construction of commercial buildings (Home Innovation Research Labs, 2015). The current version, 4.0, was launched in November 2013 and is a voluntary rating system for new and existing buildings, neighborhood development, and schools (USGBC, 2015). Specifically, with respect to C&D recycling, LEED version 4.0 requires the development and implementation of a C&D waste management plan. At least five materials must be targeted for diversion as part of the plan, and the project teams must specify whether these materials will be separated or mixed. The plan must also describe where the materials will be taken and how the recycling center will process them. In addition, points can be earned through reduction of total construction waste materials generated per square foot of a building’s area or diversion by salvage or recycling.

Green Globes

Green Globes certification was established in 2004 in the United States and is administered by the Green Building Initiative (ECD Energy & Environment Canada Ltd., 2004a). Based on the United Kingdom’s BREEAM and developed by the Canadian Standards Association, it was initially created to assist the National Association of Homebuilders (NAHB) in promoting its Green Building Guidelines for Residential Structures. There are currently two certification programs: Green Globes New Construction and Green Globes Continual Improvement of

Existing Buildings. The Green Globes New Construction assessment can be used for commercial, institutional, and multifamily residential buildings. Among its core criteria and requirements for certification are sustainable materials management and seven environmental components or assessment areas: management, site, energy, water, materials & resources, emissions, and indoor environment (Martin et al., 2013). Green Globes includes credits for Building Durability, Adaptability and Disassembly, and Reduction, Reuse & Recycling of Demolition Waste.

Living Building Challenge

The Living Building Challenge is an international sustainable certification program that provides a framework for the design and construction of buildings, including residential and commercial projects (International Living Future Institute, n.d.). It was launched in 2006 by the International Living Future Institute. Among its criteria is a requirement for certified projects to reduce or eliminate waste during the entire life cycle of buildings, and to identify ways to integrate waste back into industrial or natural nutrient loops. Table 4-2 provides the required amount of material that must be diverted from disposal during construction under the Living Building Challenge.

Table 4-3. Living Building Challenge Material Diversion Requirements (International Living Future Institute, n.d.)

Material	Minimum Percentage Diverted
Metal	99
Paper and cardboard	99
Soil and biomass	100
Rigid foam, carpet, insulation	95
All others—combined weighted average	90

National Green Building Standard

A national standard definition for green homes was developed by the NAHB and the International Code Council (ICC). To date, over 50,000 households in the United States have the ICC 700 NGBS certification, and the standard has been approved by the American National Standards Institute (ANSI) (NAHB, 2015). Projects adhering to this standard are evaluated on their resource efficiency, energy efficiency, and water efficiency; indoor environmental quality; lot and site development; and operation, maintenance, and building owner education. Included are requirements related to the quality of construction materials and waste, reused or salvaged materials, recycled-content building materials, recovered construction waste, renewable materials, resource-efficient materials, and local materials.

4.2.2 Green Building Material Specifications in Various Certification Programs

One indication of the progress that green building certification systems are making is evidenced by the emergence of green products for construction. Table 4-3 provides examples of green product requirements from three different green building certification programs (Wang et al., 2012).

Table 4-4. Select Building Component and Product Guidelines from Green Building Certification Programs[a] (Wang et al., 2012)

Building Component and Product Guidelines	LEED (USGBC, 2015)	National Green Building Standard (Home Innovation Research Labs, 2015)	Green Globes (ECD Energy & Environment Canada Ltd, 2004b and Green Building Initiative, Inc., 2015)
		Building Component Specific Requirements	
Foundations	≥ 50% of the building component must be extracted, processed, and manufactured locally (≤ 100 miles); concrete that consists of at least 30% fly ash or slag used as a cement substitute and 50% recycled content or reclaimed aggregate OR 90% recycled content or reclaimed aggregate.	≥ 50% of the footprint uses green materials such as frost-protected shallow foundations, isolated pier and pad foundations, deep foundations, post foundations, or helical piles as opposed to concrete, which is the most common material for foundations.	Credit is given for the life-cycle assessment of the building envelope, which could include concrete with recycled components.
Framing	≥ 90% of each framing component must follow optimum value engineering (OVE) measures in exterior walls and common walls.[b]	≥ 75% of the gross exterior wall area with green materials such as adobe, concrete and/or masonry, logs, or rammed earth as opposed to traditional wood, engineered wood, or structural steel.	Green product examples include OVE wood framing and cold-formed steel framing, modular sizing of openings in walls, open-web steel joints, castellated and cellular steel beams.
Flooring	100% of the flooring products must achieve the threshold level of compliance with emissions and content standards.	Prefabricated components for ≥ 90% system; prefinished hardwood flooring; ≥ 50% is third-party certified to NSF/ANSI 332, which certifies the sustainability of resilient flooring products across their entire product life cycle.	Green product examples include post-tensioned concrete floors; composite steel/concrete floors as opposed to conventional concrete floors.
Roofing[c]	Use materials that have specific solar reflectance index values based on slope or install a vegetated roof.	Prefabricated components for ≥ 90% system, ≥90% of roof surface constructed with Energy Star cool roof certification or equivalent, or a vegetated roof.	≥ 40% of roof surface is vegetated and/or has a high solar reflectance index.

(continued)

Table 4-3. Select Building Component and Product Guidelines from Green Building Certification Programs[a] (Wang et al., 2012) (continued)

Building Component and Product Guidelines	LEED (USGBC, 2015)	National Green Building Standard (Home Innovation Research Labs, 2015)	Green Globes (ECD Energy & Environment Canada Ltd, 2004b and Green Building Initiative, Inc., 2015)
Biobased Products	At least 25%, by cost, of the total value of permanently installed building products in the project must meet the Sustainable Agriculture Network's Sustainable Agriculture Standard. Bio-based raw materials must be tested using ASTM Test Method D6866 and be legally harvested, as defined by the exporting and receiving country.	Two types of the following are used for at least 0.5% of the project: certified wood; engineered wood; bamboo; cotton; cork; straw; natural fiber products made from crops; products with minimum biobased contents of the USDA 7 CFR Part 2902; other biobased materials with a minimum of 50% biobased content.	Credit can be given for third party certifications that focus on bio-based products.
Wood-based Products for Trim, Cabinetry, Millwork, Walls, Floors, or Roof	Wood products must be certified by the FSC or USGBC-approved equivalent.	Minimum of 2 certified products from the following: American Forest Foundation's American Tree Farm System; Canadian Standards Association's Sustainable Forest Management System Standards; FSC; Program for Endorsement of Forest Certification Systems; Sustainable Forestry Initiative Program.	≥ 10% is third-party certified by the following: American Forest Foundation's American Tree Farm System; Canadian Standards Association's Sustainable Forest Management System Standards; FSC; Program for Endorsement of Forest Certification Systems; Sustainable Forestry Initiative Program.
Carpet	All carpet must meet the testing and product requirements of the Carpet and Rug Institute Green Label Plus program and meet maximum VOC concentrations established for California.	≥ 50% to be third-party certified to NSF/ANSI 140, a sustainability assessment for carpet, that evaluates carpet based on public health and environment; water and energy efficiency; biobased, recycled content materials and environmentally preferable materials; manufacturing; reclamation and EOL management; innovation.	≥ 10% to be third-party certified or have Environmental Product Declarations that minimally include cradle-to-grave scopes.

(continued)

Table 4-3. Select Building Component and Product Guidelines from Green Building Certification Programs[a] (Wang et al., 2012) (continued)

Building Component and Product Guidelines	LEED (USGBC, 2015)	National Green Building Standard (Home Innovation Research Labs, 2015)	Green Globes (ECD Energy & Environment Canada Ltd, 2004b and Green Building Initiative, Inc., 2015)
Insulation	≥ 90% of insulation's component to have been tested and found compliant with the California Department of Public Health Standard Method V1.1–2010, using CA Section 01350, Appendix B for VOC emissions.	≥ 50% to be third-party certified to EcoLogo CCD-016 for environmental impact in materials; energy; manufacturing and operations; health and environment; product performance and use; and product stewardship and innovation.	≥ 10% to be third-party certified or have EPDs that minimally include cradle-to-grave scopes.
Interior Wall Coverings	≥ 90% of a wall covering's component to have been tested and found compliant with the California Department of Public Health Standard Method V1.1–2010, using CA Section 01350, Appendix B for VOC emissions.	≥ 50% to be third-party certified to NSF/ANSI 342, a sustainability assessment for wall coverings that evaluates raw material inputs; indoor air quality; product recyclability; energy use.	≥ 10% to be third-party certified or have EPDs that minimally include cradle-to-grave scopes.
Gypsum Drywall	All gypsum board must meet the testing and product requirements established in accordance with California Department of Public Health Standard Method v1.1–2010.	≥ 50% to be third-party certified to ULE ISR 100 for environmentally preferable gypsum wallboard and panels.	≥ 10% to be third-party certified.

(continued)

Table 4-3. Select Building Component and Product Guidelines from Green Building Certification Programs[a] (Wang et al., 2012) (continued)

Building Component and Product Guidelines	LEED (USGBC, 2015)	National Green Building Standard (Home Innovation Research Labs, 2015)	Green Globes (ECD Energy & Environment Canada Ltd, 2004b and Green Building Initiative, Inc., 2015)
		Product Guideline	
Life Cycle Analysis (LCA)	Conduct a life-cycle assessment of the project's structure and enclosure that demonstrates a minimum of 10% reduction, compared with a baseline building, in at least three of six impact categories, one of which must be global warming potential; (2) depletion of the stratospheric ozone layer; (3) acidification of land and water sources; (4) eutrophication; (5) formation of tropospheric ozone; (6) depletion of nonrenewable energy resources.	LCA tool is used to select environmentally preferable products/assemblies, or an LCA is conducted on the entire building; 2+ products with the same intended use are compared based on LCA and the product with at least a 15% average improvement is selected. The environmental impact measures to be considered are chosen from the following: (1) fossil fuel consumption, (2) global warming potential, (3) acidification potential, (4) eutrophication potential, (5) ozone depletion potential.	The Athena Impact Estimator or another LCA tool should be used during the design of the building.

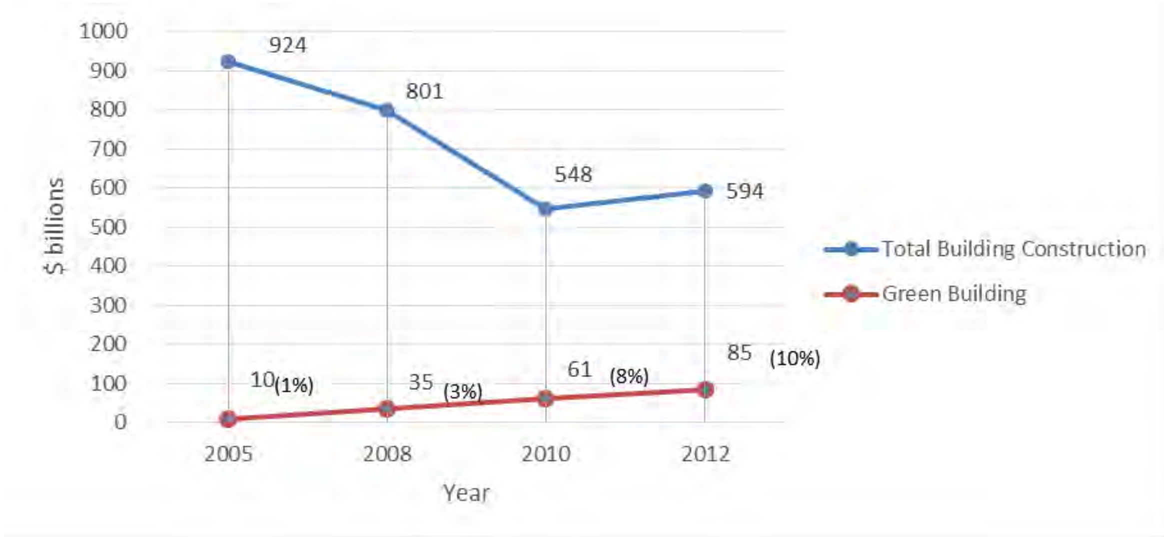
[a] A comparison with the Living Building Challenge is not provided because details are available only to members of the International Living Future Institute.

[b] Optimal value engineering (OVE) consists of designing wood-framed homes or additions with advanced framing techniques. These techniques reduce the amount of lumber typically wasted when constructing a building, while maintaining structural integrity and meeting the building code. Advanced framing techniques also allow for more insulation in the walls, which improves energy efficiency and comfort.

[c] Asphalt shingles are the most common roofing material in the United States. The solar reflectance of all commercial asphalt shingles is low. Premium white shingles are only about 30% reflective, and other colors reflect even less.

4.3 Impact of Green Materials on the Building Materials Market

According to the 2013 Dodge Construction Green Outlook report, the demand for green building products has risen as owners look for materials to help them meet their sustainability goals (McGraw-Hill Construction, 2012). Figure 4-2 shows the increase in spending on green building versus the reduction in total building construction spending during 2005 through 2012. Expenditure in the green building market increased from 1% in 2005 to approximately 10% in 2012, with indications that the market will continue to grow (McGraw-Hill Construction, 2012). In 2016, overall green building market value is projected to be between $204 billion and $248 billion. Tables 4-4 and 4-5 present the projected values for the nonresidential and the residential sectors.



Note: McGraw-Hill Construction (MHC) Green Building market size is based on MHC construction market forecast. McGraw-Hill Construction Dodge project data are substantiated by additional research, analysis, and surveys conducted by McGraw-Hill Construction between 2005 and 2013. Building codes, legislation, and policies were also used in determining market estimates. Green buildings are defined as ones built to LEED standards, an equivalent green building certification program, or one that is energy and water efficient and addresses resource efficiency and/or improved environmental quality. Projects that include only a few green building products (e.g., HVAC, waterless urinals) or that only address one aspect of green building, such as energy efficiency, were not included in these calculations.

Figure 4-2. Increase in Green Building Market Value Compared with Total Building Construction Market Value (McGraw-Hill Construction, 2012; U.S. Census Bureau, 2015)

Table 4-5. Green Building Market Value for the Nonresidential Sector (2005–2016) Compared with the Total Nonresidential Construction Market Value (McGraw-Hill Construction, 2012)

		Green Market	
Year	**Overall Nonresidential Market ($ Billion)**	**$ Billion**	**Upper Estimate % of Market**
2005	172	3	—
2008	212	25	—
2010	153	47	—
2011	147	60	—
2012	136	60	—
2013	142	64–68	45–48
2016	240	115–132	48–55

Table 4-6. Green Building Market Value for the Residential Sector (2005–2016) Compared with the Total Residential Building Construction Market Value (McGraw-Hill Construction, 2012)

Year	Single-Family Residential Market ($ Billion)	Green Market $ Billion	Green Market Upper Estimate % of Market
2005	315	7	—
2008	122	10	—
2010	100	14	—
2011	97	17	—
2012	123	25	—
2013	153	34–38	22–25
2016	306	88–115	29–38

> By 2016, spending related to green buildings was expected to be up to 55% for nonresidential construction and up to 38% for residential construction.
>
> The uncertainty in these estimates was not evaluated in the 2013 Dodge Construction Green Outlook Report (McGraw-Hill Construction, 2012). However, for discussion purposes, the market trend examples in Sections 4.3.1 to 4.3.3 assume the growth trend in the green building sector to be 22% to 55%.

With a 45% to 55% and 22% to 38% market value increase in green building over a decade for the nonresidential and the residential sectors, respectively, the impact on the production and use of conventional materials as replaced by green building materials is expected to be significant in the coming decades. Construction in the nonresidential sector, in particular, is predicted to play the largest role.

Which conventional material markets are affected by this increase in green building will depend primarily on the requirements of the certification programs. Other factors that influence the adoption of green building materials include government regulations, changes in energy costs, increasing awareness of the benefits of green technologies, decrease in the costs of green building materials, product improvements, changes in construction design, and higher resale value of green buildings.

4.3.1 Market Trends Example 1—Recovered Aggregates versus Natural Aggregates

With the growth in the green building sector, the construction industry is increasingly seeking materials that have lower life cycle environmental impacts. Due to the competitiveness in price and quality of recovered aggregates, aggregate recycling has been economically viable in locations where C&D from replaced or reconstructed old roads and buildings is abundant and where there are limitations on the use of landfills. Recovered aggregates may add strength to the overall composite material or provide a low-cost extender that binds with more expensive cement or asphalt to form concrete. Aggregates are also used to aid with differential settling as a base material under foundations, roads, and railroads. Figure 4-3 presents the production trends for aggregates (USGS, 2000).

> The supply of materials like recycled aggregates that are industrial byproducts or C&D is limited by the corresponding industrial and construction trends.
>
> One of the main sources of recovered aggregates is predicted to be C&D from concrete structures. Mobile recycling facilities have been used to recover material on-site, thereby reducing transportation costs and environmental impacts associated with transportation.

Using the range of green market share percentages presented in Tables 4-4 and 4-5 and the production trends for aggregates shown in figure 4-3, and assuming that the recovered aggregate trends mirror the trends in the overall green building sector, 22% to 55% of the total amount of aggregate material produced in 2016 (i.e., ~600 million to 1.5 billion metric tons) could be recovered aggregate destined for green building. This transition to greater use of recovered materials would represent a reduction in environmental impacts associated with the mining, processing, and storage of virgin aggregates. Mining can degrade air quality through air emissions, disturb areas of land, and impact surface and groundwater quality. Other environmental and social benefits associated with recovered aggregate use may include reduced traffic on new or existing roads to and from aggregate quarries and aesthetic degradation caused by both active and abandoned mine sites.

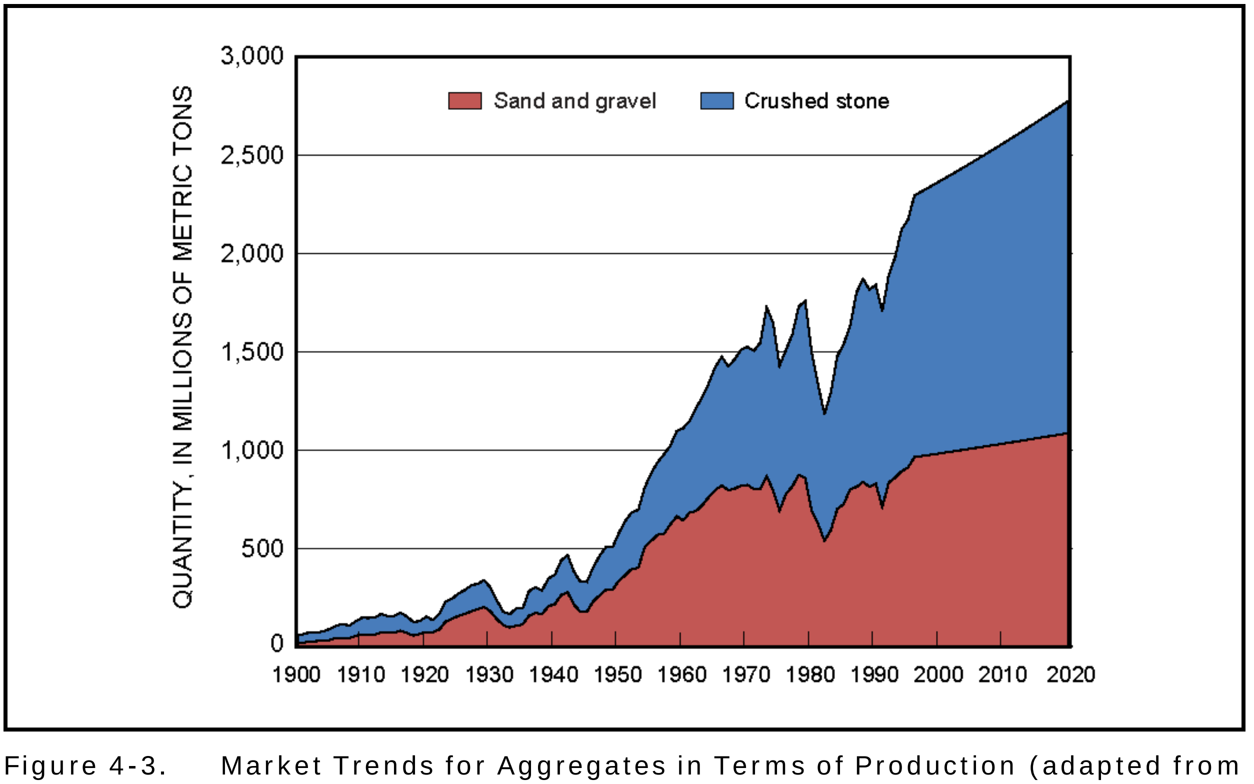


Figure 4-3. Market Trends for Aggregates in Terms of Production (adapted from USGS, 2000)

4.3.2 Market Trends Example 2—Green Building Product Labels

Product labels sometimes are given to materials attempting to indicate lower life-cycle environmental emissions than conventional materials in the market. Various product labels exist, and in response to Executive Order 136933, "Planning for Federal Sustainability in the Next Decade," which promotes sustainable acquisition and procurement of products and services by federal agencies, the USEPA has provided recommendations of specifications, standards, and ecolabels to be used in federal purchasing. This section does not attempt to endorse a particular product label but merely reflects the characteristics of the most common ones in the United States: FSC, Green Seal, formaldehyde-free insulation, and GREENGUARD. Table 4-6 summarizes the main characteristics of these labels.

> The growth of green building certified materials, which are those with green building product labels, is tied to the growth of green building certification, which credits the use of materials with product labels.
>
> With an increasing number of green certified materials, the release of environmental contaminants during the life cycle of the product, including recycling, will be minimal, as will be the infrastructure requirements to deal with these contaminants.

Table 4-7. Key Characteristics of the Green Building Product Labels Most Prevalent in the United States

Key Characteristics	Product Labels: FSC	Green Seal	Formaldehyde-free Insulation	GREENGUARD
Definition	Third-party certification body	Third-party certification body	Manufacturer claim	Third-party certification body
Start year and geographical coverage	1994, global	1989, United States	Not applicable	2001, global
Product/Material	Wood	Better known for certification of paints, coatings, and windows, but covers 375 products and service categories.	Insulation material	10,000 products
Description	Certification program with two main components: (1) certification of responsible forest management and (2) chain-of-custody certification, which is available to all companies that process or sell forest products.	Sustainability standards for products, services, and companies are based on life-cycle research.	Testing that demonstrates the absence of formaldehyde in the product.	GREENGUARD Indoor Air Quality Certification relies on test res"ults to demonstrate that products meet strict chemical emissions limits and are designed for use in office environments and other indoor spaces.
Life Cycle Stage Targeted	The entire life cycle from sawmills and fabricators to distributors and retailers.	Entire life cycle	Not applicable	
Source	Sullivan & Kahn (2013)	http://www.greenseal.org/	Various	http://greenguard.org/en/index.aspx

Figure 4-4 uses data presented in the 2011 Green Building Market and Impact Report (GreenBiz, 2011). While the use of FSC-certified wood increased in all categories from 2009 to 2010, decreases were observed from 2010 to 2011, which could be a result of the reduction in the overall building markets that was illustrated previously in Tables 4-4 and 4-5.

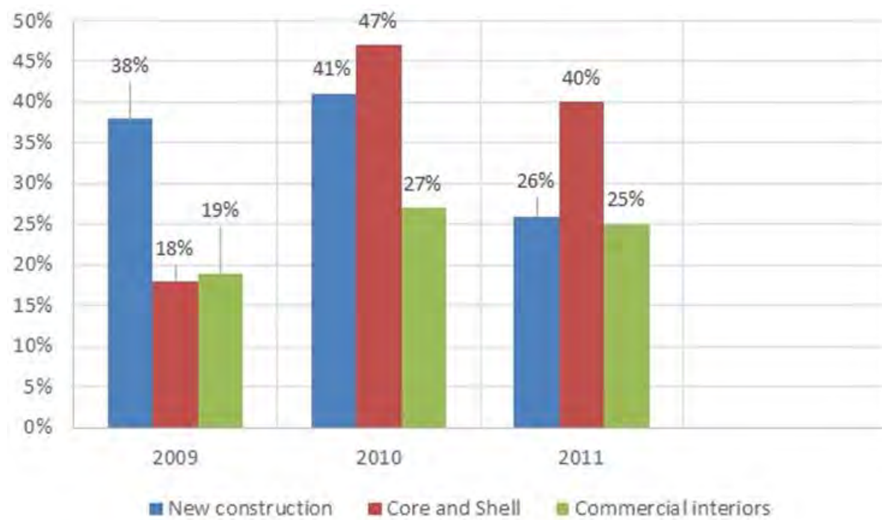


Figure 4-4. Use of FSC-Certified Wood in LEED Projects (GreenBiz, 2011)

In addition to LEED, other green building programs acknowledge and incorporate FSC certification, including model green building codes and other voluntary standards. The Living Building Challenge, for example, requires FSC certification for all virgin wood used in building construction. Regional green building programs that focus on residential construction provide additional market incentives for FSC-certified products. Examples include California's Build It Green; Earth Advantage based in Portland, Oregon; the Seattle area's Built Green program; the Chicago Green Home Program; and Minnesota Green Star. Additionally, many companies have policies that state a strong preference for FSC-certified products, including Home Depot, Office Depot, Kimberly-Clark, and Hewlett Packard (FSC, 2014).

4.4 Green Building Materials Recycling

C&D material recycling technologies may be impacted or require modifications when the characteristics of the green building material differ significantly from those of conventional materials. However, many green building products primarily differ from conventional products in the way they are sourced (e.g., FSC-certified wood) and do not necessarily include new or different materials. Therefore, existing recycling technologies and practices still apply to many of these materials. The main difference in these green building materials is that they have lower life-cycle environmental impacts. According to BuildingGreen (2015):

> *The surest way to reduce the environmental impact of a material is simply to use less, usually by design.*
>
> *There are products that serve their function using less material than the standard solution and products that are especially durable and therefore won't need replacement as often. Efficient use of materials also means moving from linear "cradle-to-grave" to cyclic "cradle-to-cradle" use of materials.*

If, by design, the recyclability of green building materials was expanded, the potential increase in the stream of recovered C&D could lead to an expansion of the existing infrastructure to accommodate higher material flows.

However, the number of times that a material can be recycled before final disposal varies depending on its physical and chemical characteristics and the changes that occur during remanufacturing. Therefore, repeated recycling of certain C&D materials could potentially impact their ability to be recycled in the future. In the future, the increased popularity of green building programs may also spur development of new recycling technologies as well as more durable building materials and products capable of preserving functional characteristics through multiple recycling processes. Table 4-7 provides information on the recyclability of various materials based on current technological conditions.

Recycling of some types of emerging green materials frequently encounters two significant issues: (1) there are not enough facilities able to recycle them, and (2) there is not enough of the emerging material to recycle and thus create a market that enables the recycling to be economically viable. Recycling of existing materials is of particular importance when the virgin materials are scarce, or the processes used to manufacture the new materials are resource intensive. For example, the silicon used to make photovoltaic cells is abundant, but manufacturing a silicon-based solar cell requires a significant amount of energy. The source of that energy ultimately determines how large the cell's carbon footprint is. However, green building materials are increasingly being developed with the goal of reducing their environmental footprint, which includes finding EOL recycling options.

Table 4-8. Summary of Factors Affecting Materials Recyclability (Adapted from GD Environmental, 2016; Glass Packaging Institute, 2016; Scott, 1996; Steel Recycling Institute, 2014; The Aluminum Association, 2016)

	Factors Affecting Recyclability		
Materials	Number of Cycles	Recycling Process Characteristics	Type of Material
Metals	Number of cycles does not affect the physical and chemical characteristics.	Contamination during the process may degrade quality. Proper sorting is key.	All metals.
Glass	Number of cycles does not affect the physical and chemical characteristics.	Glass color mixing should be avoided. Proper sorting is key.	Some glass cannot be recycled, e.g., window panes, some glassware, and light bulbs.
Plastics	After one cycle the quality degrades for most plastics, and down-cycling to nonrecyclable materials such as plastic lumber may be required.		All plastics.

5. ENVIRONMENTAL AND HEALTH CONSIDERATIONS ASSOCIATED WITH C&D RECOVERY

Although C&D recovery provides numerous environmental benefits (e.g., reduced consumption of virgin construction materials, emissions reductions, smaller landfill space demands), potential risks associated with the processing and recycling of these materials must be considered. As described in USEPA (2004), there are several hazardous or potentially harmful materials that may be present in C&D that can cause harm or pose a risk to human health and the environment, if improperly handled. These include asbestos, lead-based paint (LBP), polychlorinated biphenyls (PCBs), mercury, and treated wood. Federal and state regulations address the handling of these materials during both the construction and demolition process, and as part of disposal and recovery. In addition to complying with these regulations, it is necessary for the C&D contractor and recycler to be aware of the potential human health and environmental issues and to implement best management practices.

> EPA has prepared a methodology for evaluating the beneficial use of industrial non-hazardous secondary materials, including C&D. This voluntary methodology is available at https://www.epa.gov/sites/production/files/2016-10/documents/methodology_for_evaluating_beneficial_use_of_secondary_materials_4-14-16.pdf.

5.1 Materials and Constituents of Potential Concern in C&D

Some products historically used in building construction contain chemicals, elements, or minerals that cause harm or pose a risk to human health and the environment if improperly managed. Additionally, some materials used in modern buildings contain chemicals that may also pose a risk. Examples include mercury lighting, batteries, some types of paints, treated wood, and various construction chemicals. Table 5-1 provides an overview of some example materials that should be considered during any construction or demolition project. The possible transfer of pollutants into recycled products from some of these materials is described in greater detail in Section 5.2.

The best approach to minimize the contamination of C&D destined for recovery is to remove materials of potential concern prior to starting demolition or renovation work—or, in the case of construction projects, to segregate and manage them separately. Several U.S. states have developed policy and educational guidance for the removal of specified building components.

> The use of asbestos, LBP, PCBs, and other such products has largely been banned or discontinued, but they remain in the built infrastructure and must be handled appropriately when present during demolition and renovation work.

Table 5-1. Partial List of Possible Contaminants in C&D Waste Streams and Some Potential Sources (EES, 2004)

Potential Contaminant	Possible Locations of Contaminants
Asbestos	Heat and acoustic insulation, flooring, roofing, noncombustible materials, ducts, etc.
Lead	Lead paint, lead objects, lead acid batteries, roof flashings, pipes
Mercury	Light bulbs, high-intensity lamps, thermostats, switches
PCB	Lighting ballasts, caulk, paint
Batteries	Emergency lights, alarm systems
Treated wood	Wood, especially outdoor structural wood
Refrigerant	Appliances, dehumidifiers, vending machines, air conditioners, heat pumps, ice machines

Minnesota is an example of a state that has issued a mandatory pre-renovation/demolition environmental checklist, listing numerous items and materials that must be removed prior to initiating a renovation or demolition project (MPCA, 2009). Florida has a guidance document that provides an overview of materials that should be removed, with a checklist for demolition contractors to follow as part of the pre-demolition process (EES, 2004; Sheridan et al., 2000). Best management practices for general construction and demolition typically also include extensive information on removing hazardous materials (DGS, 2007; IDNR, 2008; OGS, 2014).

Although removing materials of concern before they become mixed with other C&D materials best addresses the objective of producing a clean recycled stream, unwanted materials will, at times, find their way into C&D processing and recycling facilities. Because C&D processing may distribute unwanted constituents into recovered products (see Section 5.2), facility operators must develop and maintain plans for identifying and removing materials of concern prior to processing. Depending on the state, these requirements might be included as part of the site′s operating permit. Common steps to achieve these objectives include providing clear and visible signage of the facility′s acceptance policy to contractors dropping off materials at the facility, and inspecting each load of material as it arrives at the facility (at the gatehouse).

Because not all materials will be visible to the inspector at the gatehouse, additional inspections should take place where the debris is unloaded from the container or vehicle. A common regulatory requirement integrated into a site′s operation permit is the use of spotters to inspect each incoming load after the load is discharged onto the tipping floor. Many states require that spotters undergo periodic training on the identification of problematic materials and procedures for their safe management. Facility operators often track C&D loads through job tickets so that haulers (and generators) can be notified and held responsible should unacceptable materials be brought to a site.

The products from a C&D recovery facility may require testing to meet regulatory requirements or customer demands; thus, operators often know the chemicals of concern and can be especially aware of their presence in the material. With this knowledge, operators can best avoid or redirect sources of debris prior to processing. For example, in the case of recovered wood products, operators often reject or redirect loads of treated wood or painted wood, so they do not commingle with other wood products destined for size reduction and recovery.

5.2 Cross-Media Pollution and Exposure

This section discusses the potential for cross-media contamination as a result of processing a select set of C&D materials. Although various materials may involve the transfer of chemicals, this section reviews wood, drywall, asphalt shingles, and C&D fines. Because harmful chemicals may be transferred from C&D streams into recycled end products, this discussion addresses the potential for cross-media contamination during the recovery process.

> While C&D recovery provides a variety of benefits over the consumption of virgin resources, those making decisions about community material management should be aware of the potential for cross-media transfer of pollutants.

5.2.1 Facility Considerations

Workers at C&D processing facilities may be exposed to several different types of occupational hazards that could impact their health and safety, including dust, LBP, and asbestos. Therefore, proper equipment and health and safety training are necessary to protect processing facility workers, given that harmful materials may be present in a C&D load. Existing federal (Occupational Safety and Health Administration) and state regulatory provisions address occupational hazards and preventive measures that should be taken to prevent exposures to harmful materials, although these provisions are typically not specific to the C&D recovery industry. C&D processing facilities are responsible for understanding general provisions for health and safety and for providing worker training that specifically identifies and explains the situations they may encounter and how to protect themselves while on the job.

As previously discussed, a crucial step in preventing processing facility workers from exposure to harmful materials begins at the job site, where the deleterious materials are identified and removed and managed prior to the construction, demolition, or renovation work. The removal of harmful materials from C&D is a responsibility of the C&D contractor or party delivering C&D to the processing facility. It is paramount that facilities have in place a specific plan that outlines methods for preventing unwanted materials from arriving and explains the proper operational procedures to identify and remove contaminants safely before processing.

Permitted facilities are typically required to have a site-specific operation plan that outlines best management practices and methods to keep employees safe. Included with such plans are methods for identifying and addressing contaminants observed on the tipping floor, steps to follow in case of emergencies, operational procedures for equipment, maps, and provisions to allow safe navigation of the facility, and information on personal protective equipment (PPE). PPE commonly used in C&D recovery facilities includes dust masks and other methods of respiratory protection, equipment to protect against physical contact with C&D (i.e., gloves), hearing protection, and other standard equipment such as steel-toe boots, hard hats, and high-visibility vests.

Assurance Safety Consulting (ASC) prepared a health and safety manual for Construction & Demolition Recycling Association (CDRA)-member C&D recovery facilities to help develop and implement health and safety policies for employees and administration (ASC, 2013). The manual provides a list of safe work practices to be implemented in various situations during C&D recovery facility operation. The guidelines for employees' health and safety include following all the safety rules and practices provided by the employer, working on the specific tasks assigned, reporting any unsafe condition, using proper tools, following good housekeeping and hygiene practices, familiarizing oneself with location and content of material safety data sheets, using proper PPE, and being aware of the premises. The manual also includes guidelines for safety at the tipping floor, during emergencies, near heavy equipment (such as blind spots for heavy equipment used in the facility), equipment lockout and tag out, machine guarding, and fall protection policies.

5.2.2 Material-Specific Considerations

Treated Wood

Treated wood is a ubiquitous construction material in much of the country, and wood products may be treated with various chemicals including creosote, pentachlorophenol, chromated copper arsenate (CCA), alkaline copper quaternary, borates, copper azole, cyproconazole, and propiconazole. Creosote and pentachlorophenol are used primarily in utility poles and railroad ties, so most C&D processing facilities that produce a mulch end product will not accept these treated wood products. However, some facilities may accept utility poles or railroad ties for other reuse opportunities (e.g., retaining walls, building purposes).

The treated wood type that has received the most attention with regard to the C&D recovery industry is CCA. CCA-treated wood can be difficult to distinguish from other types of commonly recovered C&D wood. Although the use of CCA-treated wood has been discontinued for most U.S. residential construction applications since January 2004, much of this material remains in service. CCA-treated wood contains high concentrations of arsenic, chromium, and copper; arsenic has been the chemical of most concern. Solo-Gabriele et al. (1998) reported average arsenic concentrations of 1,200 mg/kg and 33,000 mg/kg for unburned CCA-treated wood and ash produced from combusting CCA-treated wood, respectively.

The presence of CCA-treated wood in a C&D boiler fuel product can also be problematic. Many boiler facilities limit the amount of CCA-treated wood that can be included in their fuel product. Some states allow the combustion of creosote and other treated wood products in commercial or industrial solid waste incinerators, which must meet the stringent air emission standards of the Clean Air Act (CAA) Section 129 (where air emissions and ash management are stringently controlled). As discussed in Section 3.4.5, the USEPA recently modified the applicable air emission standards (i.e., CAA Section 112) for biomass facilities, and biomass facilities must now comply with the less stringent, CAA Section 112, standards. However, the presence of CCA-treated wood in a fuel product can affect the biomass facility's ability to meet CAA Section 112 standards related to the fuel product.

The presence of CCA-treated wood in a fuel product can also dramatically alter the ash characteristics; Solo-Gabriele et al. (2002) observed that if mixed wood waste contains more than 5% of CCA-treated wood, the ash generated from its combustion would leach enough arsenic to be characterized as a hazardous waste based on the toxicity characteristic. Even in small amounts, the elevated metals concentrations in the ash resulting from CCA-treated wood could limit land disposal options.

Because of the concerns CCA-treated wood poses, many states require, as part of regulatory permit conditions, that CCA-treated wood is separated from other wood and managed distinctly (not recycled). The challenge in meeting these requirements is to identify the CCA-treated wood for segregation properly. Identifying treated wood can be accomplished to some extent through visual means if operators are trained, and sound inspection practices are implemented. Furthermore, the Florida Department of

Environmental Protection (FDEP) published a best management practices guide for identifying and removing CCA-treated wood from the C&D stream (FDEP, n.d.). The guide discusses several specific identification strategies that include the use of stains and X-ray fluorescence (XRF) detectors, as well as arsenic test kits and laser-based technologies.

The phase-out of CCA from the residential market has resulted in the introduction of a new suite of replacement preservatives. Copper compounds and, in some cases, added chemicals provide wood preservation and protection from biological decay.

Lead-Based Paint

Although LBP was banned from use in the United States, the presence of lead in painted wood from older buildings remains a concern in many areas of the country. If present in sufficient quantities, wood with LBP may pose some of the same issues as CCA-treated wood. Lead from painted wood may leach into soil and groundwater (although lead tends to be much less mobile than arsenic), and combustion of fuel products with high lead levels may violate air emission standards.

Visual screening and XRF analyzers can be used to identify materials coated with LBP. Certain wood materials have a higher likelihood of containing an LBP coating, as LBP has frequently been used to coat wood components exposed to outdoor conditions (e.g., door frames, window sills).

As part of a facility′s regulatory permit, conditions are often in place to limit the acceptance of painted wood. While the best way to ensure against contamination is to segregate all painted wood, those interested in specifically identifying lead paint can use portable XRF analyzers. R.W. Beck et al. (2010) described the use of these devices to identify painted surfaces with a concentration of lead higher than 1 milligram per square centimeter.

The presence of lead is the largest paint-associated issue affecting C&D recovery, but some specialty paints may also contain elements or chemicals of concern. PCBs have been used in some specialty paints to provide fire resistance. Cadmium has been used in pigment and mercury, tin, and zinc have been used to prevent biological growth. Many of these specialty paints will be associated with various substrates such as concrete and metal.

Drywall

Depending on adjacent C&D materials at the time of demolition and on the additives used by the drywall manufacturer, gypsum from demolition drywall may contain small amounts of LBP, asbestos, and boron. Drywall debris from older structures may contain LBP and may also contain asbestos, which was added to improve its strength, fire resistance, and noiseabsorbance. Asbestos was also added to the wall patching compounds, but the use was banned in 1977. Boron was used in several different brands of drywall as a form of fiberglass to enhance mechanical strength and as a fire retardant (SWRCB, 2016; Townsend et al., 2013). Because of concerns related to older drywall sources, many C&D recovery facilities only accept construction scrap.

Asphalt Shingles

The primary concern with the recovery of asphalt shingles is the potential presence of asbestos. Historically, asbestos was used as the fiber material by a few shingle manufacturers to provide mechanical strength and fire resistance. That said, most asbestos occurrences associated with asphalt roofing products are not associated with shingles. To fully address contamination concerns, regulatory permit requirements for shingle recyclers typically include a provision for sampling and analyzing incoming shingles loads for asbestos. A study conducted by the Construction Materials Recycling Association detected asbestos in approximately 1.5% of 27,000 samples collected from 10 facilities in six states, although the observed asbestos was due to the presence of mastic and not the asphalt shingles themselves (IWCS, 2007). Currently, dedicated shingle processing facilities or mixed C&D processing facilities may accept non-asbestos shingle loads. Facilities may test for asbestos contamination in shingles and sort out the load as described by Powell et al. (2015).

C&D Fines

As described in Section 2.3.8, C&D fines are often used as alternative daily cover (ADC) at landfills. In this use, the primary area of concern that has been noted in the industry is the potential for H_2S production because of the elevated gypsum content in C&D fines, also known as recovered screened materials (RSM), which has been observed to vary from 1% to over 25% of the total material in the fines (Musson et al., 2008). Several states have developed reuse criteria and guidance. For example, the FDEP describes sampling and analysis requirements for C&D processing facilities to demonstrate the appropriateness of an intended beneficial use of RSM (FDEP, 2011).

6. DATA GAPS AND ADDITIONAL RESEARCH OPPORTUNITIES

This section identifies data gaps and additional research opportunities that were identified during the review of the state of the practice of C&D recovery in the United States.

1. Quantifying Reuse of C&D. Insufficient information exists on quantities and types of C&D materials that are recovered for reuse. A nationwide, region-specific study that analyzes the amount and type of C&D being diverted through salvage and reuse would help community decision-makers identify the potential of, and encourage the implementation of, this practice.
2. Quantifying Recovered C&D Material Markets. With the exception of asphalt pavement, very little information appears to exist that quantifies the end uses of different recovered C&D materials. A nationwide, region-specific study that analyzes the amount of recovered C&D being diverted to different end uses would help community decision-makers identify diversion options in their area.
3. Identification of Factors that Promote Community C&D Recovery. While resources exist for estimating the total amount of nationwide C&D that is recovered versus disposed of, a detailed, large-scale analysis of factors which contribute to successful C&D recovery does not exist. A national review of public policy, economic, and social factors that promote C&D recovery would provide an additional means by which communities could increase the recovery and beneficial use of C&D.
4. Beneficial Use of C&D Fines. Based on CDRA (2015), C&D fines/RSM represents nearly 18% of the material recovered from mixed C&D processing facilities across the United States. However, there appears to be no national characterization study of this material. Also, while it is generally understood that one of the primary end uses of C&D fines is as a landfill ADC, no large-scale studies were found that document the success or challenges of this use at landfill sites across the country. Examples of pertinent questions to explore through a review of landfill case studies include, "How common is it for sites using RSM as an ADC to experience issues with the release of H_2S?" and "Do landfills using RSM generally experience less, more, or the same number of odor complaints from surrounding properties after switching from daily cover soil to an RSM ADC?"
5. Beneficial Use of Processing Residuals. Results from CDRA (2015) suggest that nearly 20% of the output of mixed C&D processing facilities is a solid waste; the use of these processing residuals as a refuse-derived fuel can significantly reduce the quantity of C&D being landfilled. A nationwide study that reviews case studies where this

beneficial use is practiced would be helpful for community decision-makers considering ways of improving C&D diversion rates.

6. Market Analysis of C&D Diverted from Landfills. Landfills may financially benefit by diverting some C&D from disposal from an airspace-preservation perspective. A nationwide, region-specific market analysis of diverting source-segregated loads of certain bulky C&D materials (e.g., concrete, shingles, LCD) with onsite processing may show that this practice could benefit the landfill owner/operator, the surrounding community, or both. These materials may provide a valuable resource because markets and material processing strategies are well established, and fewer obstacles prevent their beneficial use.

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